The Future of Engineering Education
2024 Annual Conference & Exposition
Oregon Convention Center
Portland, OR . June 23 - 26, 2024
Paper ID #42214

Board 61: Work in Progress: Teaching Logic Design with Interactive Computer Games

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Teaching Logic Design with Interactive Computer Games

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Abstract

Sum-of-Products (SOP) expressions are two-level representations of Boolean functions consisting of an OR sum of AND terms. There exist many methods of SOP synthesis, but the Karnaugh map method is the most frequently taught in undergraduate curriculum. Unfortunately, most traditional approaches to teaching Karnaugh map-based SOP minimization are not very engaging for the learner. To increase student engagement, game-based approaches to teaching are increasingly being used to supplement traditional teaching methods. There has been limited research into extending such game-based teaching approaches towards SOP minimization with Karnaugh maps. This paper proposes a game to teach Karnaugh map-based SOP minimization. The players of the proposed learning game seek to maximize the true minterms they individually cover within the Karnaugh map through a back-and-forth turn-based model. The system consists of both a two-player version between two human players and a single-player version that involves a computer opponent in place of a second human player. This game makes learning about Karnaugh map-based SOP minimization more engaging and convenient to practice. Results found significant increases in learning retention and self-reported engagement for users of both the single and two-player versions compared to conventional teaching methods. These findings underscore the potential that incorporating game design elements into instruction can have in enhancing students' understanding of topics such as SOP minimization and Karnaugh maps. These results highlight the importance of future research investigating the educational benefits of applying game-based learning to other introductory logic design topics.

Introduction

Within the field of education research, there has been a significant amount of research comparing interactive learning methods to more traditional methods [1]. Interactive learning methods typically involve the application of digital media, such as apps and games, to encourage independent, autonomous learning. Traditional learning methods, on the other hand, involve methods that rely on blackboards, lectures, books, written exercises, etc. to transmit knowledge. Past research has often found that interactive learning methods force students to remain active for long periods of time and allow students to maintain greater autonomy and independence in reasoning [2][3]. Additionally, interactive learning methods help students develop a stronger relationship with classmates and professors, especially compared to passive learning methods.

However, no study has analyzed the specific advantages and disadvantages of interactive learning when applied for concepts such as SOP minimization. This paper delves into the nuanced exploration of the advantages presented by interactive learning methods in comparison to their traditional counterparts for Karnaugh map-based SOP minimization.

Historically, educators have used different strategies to teach Karnaugh map-based Sum-Of-Product minimization. The traditional approach, prevalent in institutions of higher education, has been the didactic lecturing model, where instructors disseminate theoretical knowledge to students in a unidirectional manner. Such an approach involves instructors presenting algorithms and optimization techniques through traditional lectures, relying on textbooks and static resources as the primary instructional tools. However, this method tended to prioritize passive absorption of information, lacking the interactive and experiential elements crucial for deep understanding [4]. With the evolution of educational research in the late 20th and early 21st century, new techniques have been developed to increase active learning [5].

As pedagogical paradigms shifted towards active learning, researchers and educators sought to incorporate more engaging techniques for engineering education. Puzzle-based learning (PBL) emerged as a notable alternative, emphasizing the application of theoretical concepts to problem-solving scenarios. In our context, students actively engage with SOP minimization challenges, collaborating in groups to derive solutions. The PBL model can be used to encourage critical thinking, decision-making, and the development of problem-solving skills within the specific domain of SOP minimization [6].

Previous research has explored the use of games to teach SOP Minimization, but these games generally rely on a two-player approach for game-based learning. This paper will instead focus on a one-player approach to make a direct comparison between traditional self-learning and game-based, interactive self-learning [7].

Within the domain of computing, the application of interactive learning methodologies becomes especially pertinent. The integration of interactive learning tools in computing education has demonstrated the potential to enhance students' comprehension and retention of complex concepts. Through interactive simulations and game-based learning, students are able to actively participate in the learning process, which has been shown to increase long-term retention and engagement within the learning process [8, 9, 10].

This paper is the first to directly examine and compare the effectiveness of interactive learning versus traditional approaches to SOP minimization in increasing student engagement and retention. Through objective scores of student results with both approaches, this paper clearly establishes the importance of researching and developing new ways to adopt interactive learning even in undergraduate electrical and computer engineering education.

Background

A completely-specified **Boolean function** is a mapping $f : \{0,1\}^n \rightarrow \{0,1\}$. A Boolean function is considered incompletely specified if the corresponding output is not known for every possible input. We call the input combinations for which the output is either not known or invalid as "**don't cares**." Don't cares are highly relevant to both logic design and machine learning.

Two common representations of Boolean functions are **truth tables** and **Karnaugh maps**, as shown in Figure 1.

a	b	c	d	$f(a,b,c,d)$
0	1	0	1	1
0	1	1	1	0
1	1	1	1	1

(a) Truth table.

-	-	-	-
-	1	0	-
-	-	1	-
-	-	-	-

(b) Karnaugh map.

Figure 1: Example of a Karnaugh map and truth table for an incompletely specified function.

In logic synthesis, we seek to realize a Boolean function as a **Boolean circuit**. **Sum-of-Products** are a specific form of Boolean circuits, characterized by a level of AND gates and a level of OR gates. A Sum-of-Products (SOP) expression is a specific type of Boolean expression that is formed by the output of multiple AND gates united by one or more OR gates.

An **AND gate** is a Boolean binary gate that evaluates to 1 only if all inputs to the AND gate are 1, while an **OR gate** is a Boolean binary gate that evaluates to 1 as long as at least one input to the OR gate is 1. A **NOT gate** is a Boolean binary gate that inverts the value of a single variable. For the rest of the paper, these gates will be referred to as either Boolean or binary for simplicity.

A **Boolean literal** is a Boolean variable or its negation. A **product term** is a product of literals. A Sum-of-Products expression can also be defined as the representation of a function as a Boolean sum of the product terms.

A **minterm** is the product of literals for all input variables of the function. A **prime implicant** is a product term that cannot have all of its true minterms covered by another, larger product term. An **essential minterm** is a minterm that is covered only by a single prime implicant. An **essential prime implicant** is a prime implicant that covers an essential minterm. Figure 3 illustrates the aforementioned concepts.

By representing a truth table visually, a **Karnaugh map** can be used to simplify Boolean expressions [11]. Karnaugh maps use Gray code to enumerate the combination of literals in rows and columns. Gray code ensures that adjacent cells of the Karnaugh map differ in only a single variable. Each cell in a Karnaugh map includes either a true or false value or a don't care. By identifying sets of products on a Karnaugh map that cover true minterms, a truth table can be simplified into a Sum-of-Products expression.

The Game

The method by which this paper teaches SOP minimization is a game with which students compete to capture the maximum number of true minterms. Upon capture by either player, a true minterm's square or cell is highlighted with the player's corresponding color. Once all true minterms are captured by either Player One or Player Two, the game is over and the player with a greater number of true minterms covered wins. The player(s) can also capture true minterms occupied by the other player to both reduce their opponents score and increase their own. However, if a player captures a false minterm through any one of their moves via an incorrect Sum-of-Products, then the player forfeits the game. As such, the game encourages students to naturally discover Sum-of-Products expressions and helps students practice minimizing Karnaugh maps.

Through this game, students are able to learn and practice rather easily, but the one and two-player modes enable such learning to also be engaging. Past research has found that game-based learning is one of the most engaging methods of learning for students, and this paper attempts to prove these findings within specifically the realm of logic design education [4, 12, 13]. Previous research has used two-player approaches to gamify logic design education, but by expanding such gamification to one-player (Player vs Computer) game modes, there is potential for greater versatility and accessibility. The basis of engagement from gamified models is the aspect of healthy competition introduced to education, which in the case of a player vs player model, is limited only to sparse competition between two participants, whereas a player vs computer model enables constant competition for the human player. Such healthy competition has been shown to improve learning outcomes and student effort [14].

A **move** in our proposed game is the selection of any possible product implicant. Some moves, such as those containing products covering false minterms, will immediately lose the game when selected. Other moves, such as those consisting of non-prime implicants, are suboptimal for the player. This is because any move consisting of a non-prime implicant will cover less true minterms than its prime counterpart.

Through extensive gameplay, human players can correlate different moves, i.e., selection of product terms, with winning or losing outcomes and thereby intuitively grasp several logic design concepts *without direct instruction*, e.g. the concepts of prime implicants, essential prime implicants, incorrect product terms, and don't cares.

The method by which the software for the computer opponent makes moves is based on an algorithm designed to find all legal moves and sort them via the number of true minterms. Every move that covers a false minterm is referred to as an illegal move by the computer opponent, which means that the computer opponent does not blunder the game against the student via obvious errors. However, the computer can make mistakes by focusing on the "greediest" move at all times. This design encourages students to think beyond the move with the most number of true values (a short-term strategy that will see the computer always beat them), and instead focus on long-term moves in order to beat the computer opponent. Such thinking helps teach students how to create the simplest expression of Sum-of-Products for any given Karnaugh map, rather than just the single largest SOP, which provides useful value directly related to content in digital design curricula.

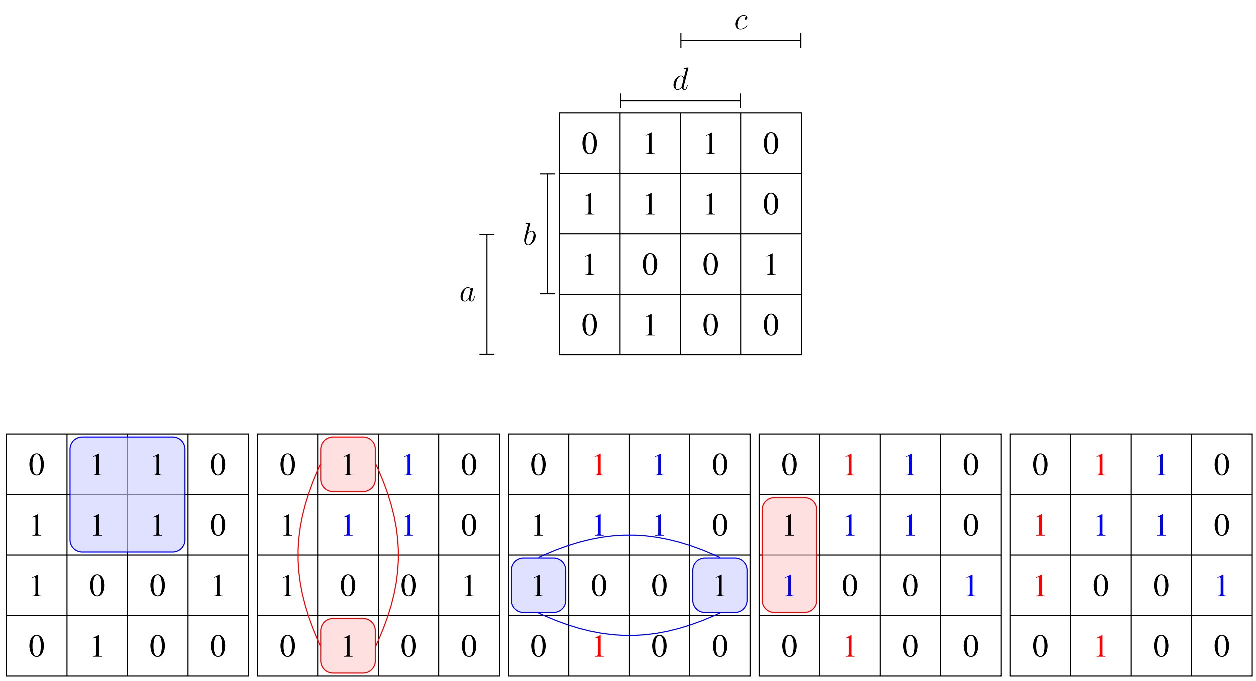


Figure 2: Gameplay example.

A hypothetical example of how this "learning game" could be used to teach Karnaugh map-based SOP Minimization can be seen with the following truth table, shown in Figure 2. Player One is represented as Blue, while Player 2 is represented as Red. If played in two-player mode, Player One would be forced to consider which moves would earn the most number of points initially. Player One could consider the move $\overline{a}d$, in order to secure the 4 squares in the top center. Player 2 could then consider one of three moves: $b\overline{c}\overline{d}$, which captures the 2 squares in the center-left, $ab\overline{d}$, which captures the two true minterms in the third row, and $\overline{b}\overline{c}d$, which captures 2 squares, including a square stolen from Player One, as shown in the second table in Figure 2. As can be seen by each of these three moves, the ideal move in any situation will always be a prime implicant. This is because any non-prime implicant will, by definition, always have a prime implicant which covers the squares that the non-prime implicant covers, among others. After Player Two makes their first move, Player One has two possible moves to make: $b\overline{c}\overline{d}$ and $ab\overline{d}$, both of which capture 2 non-essential squares and are as such identical. Assuming Player One plays $ab\overline{d}$, as shown in the third table in Figure 2, Player Two has only one move that represents a prime implicant: $b\overline{c}\overline{d}$. This move captures an uncovered square and also captures a new square from Player 2, and with Player 2's second move, all true minterms in the Karnaugh map are covered and the game is over with both Players having an equal score of 4 captured minterms. In this short example, Player 2 was able to draw the game solely because their first move consisted of an essential prime implicant

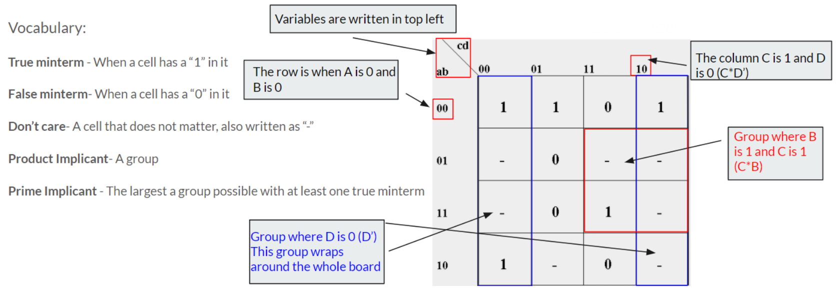


Figure 3: Karnaugh map of $\overline{d} + cb + \overline{c}\overline{d}$

($a\overline{b}\overline{c}d$ cannot be covered by any other prime implicant): if Player 2 played any other first move and both sides played ideally from there, Player 2 would always lose. Thus, a simple but generally good strategy is to always look for and pick any available essential prime implicants. In this purely hypothetical scenario, both players would learn how to find Sum-of-Products with a significant number of true minterms while also avoiding any false minterms, as well as finding essential prime implicants and non-essential prime implicants, both of which are important for Karnaugh map-based SOP minimization. As such, this game can function, in this hypothetical case study, to effectively instruct students in such a topic.

Experiment Design

To compare the advantages of using a gamified model, two groups were created, each consisting of 30 participants. The participants in both groups were high school students, generally of good academic standing, in either 11th or 12th grade from the same high school in New Jersey. The first group was exposed to Karnaugh maps via first a short video explaining the basics of how Karnaugh maps work, followed by 10 minutes provided to review a university-level lecture note. The second group also had the same short video presented to them, followed by 10 minutes to play with the educational game against the computer opponent. For the participants in the second group, each round of the game consisted of a 7-variable Karnaugh map with at least 3 zeroes and up to 8 zeroes and at least 5 ones and up to 15 ones, as shown in Figure 4. Participants in group 2 were given a rundown on basic vocabulary terms and how to play the game through the help section, as shown in Figure 4 as well as verbal instructions, but otherwise received no additional review prior to the 10-minute experience with the game.

Following the learning session, the participants in both groups were given a worksheet with 10 Karnaugh map-based SOP minimization problems to complete in 30 minutes. The participants were then asked to self-report from 1-10 how engaged they were during the learning process, and how confident they were in their ability to solve more Karnaugh map-based SOP minimization problems. These results can be viewed in Figure 5.

Results

The data collection for participants exposed to the game and for participants exposed to the review worksheet consisted of both objective and subjective measures. In general, each participant's score

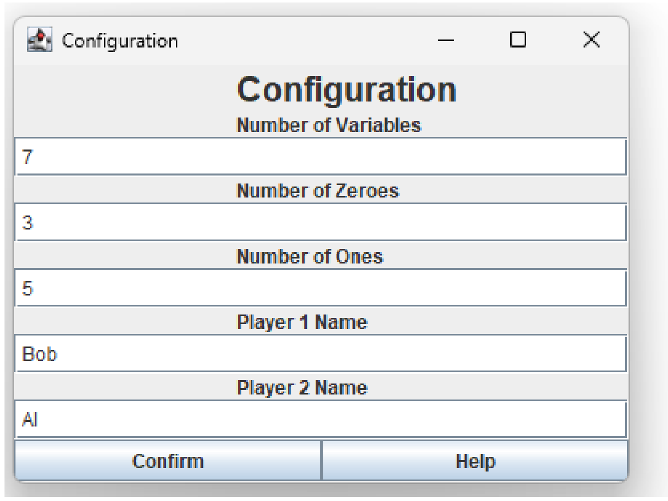
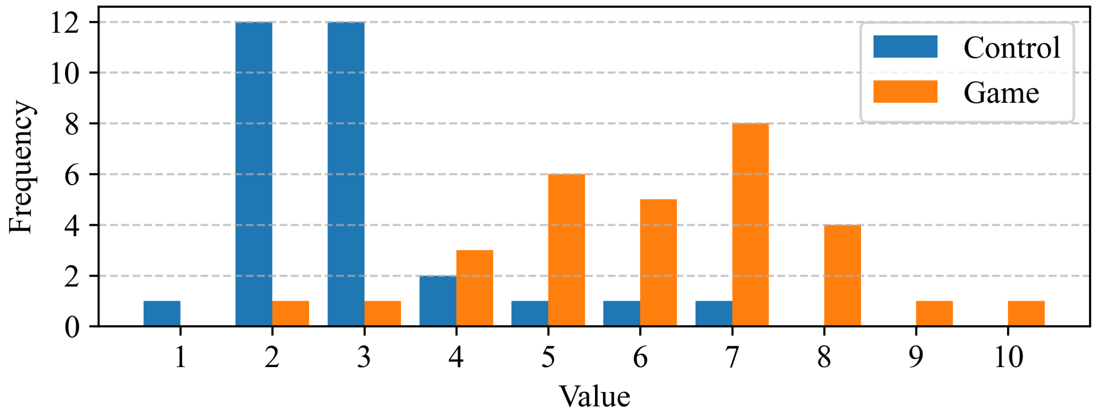


Figure 4: Configuration before starting a new game.

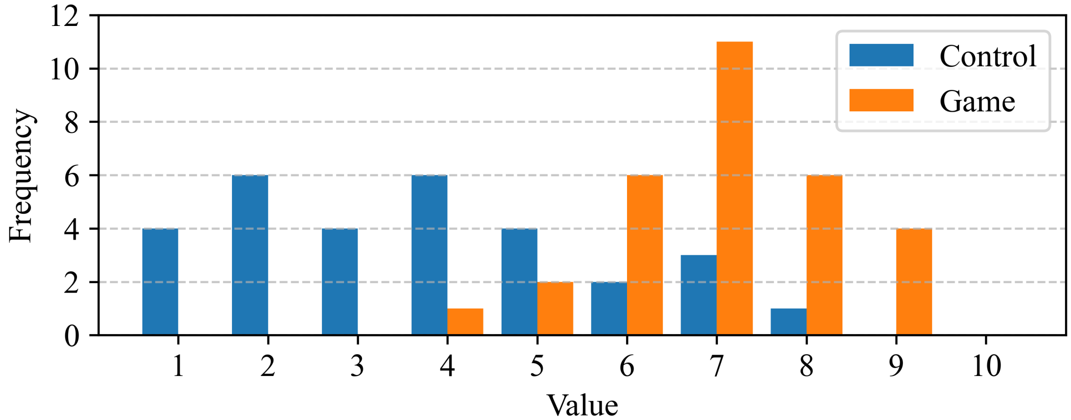
on the test following the learning process was used to measure participant's aptitude at solving Karnaugh maps. This served as an objective measure of a participant's absorption of the content taught via the video, worksheet, and/or the game. However, for the engagement and confidence levels of participants, there were no feasible methods in which to accurately and objectively measure perceived confidence and engagement. As such, the most practical method was to request participants to self-report their engagement and confidence levels on a scale of 1-10.

The results of the experiment are tabulated in Tables 1 and 2. Overall, the results of the experiment, as shown in Figure 5, demonstrate a generally higher self-reported confidence and engagement with the learning process, as well as higher objective test scores (Figure 5a), among participants exposed to the game. The difference between the mean test score of the treatment group and the mean test score of the control group is approximately 3.23 correct answers. Participants exposed to the game also had significantly higher self-reported levels of confidence and engagement than participants exposed to the review worksheet, as shown in Figure 5b and 5c. The difference between the mean confidence level of the treatment and control group was 3.26, and it was 3.14 for the engagement level.

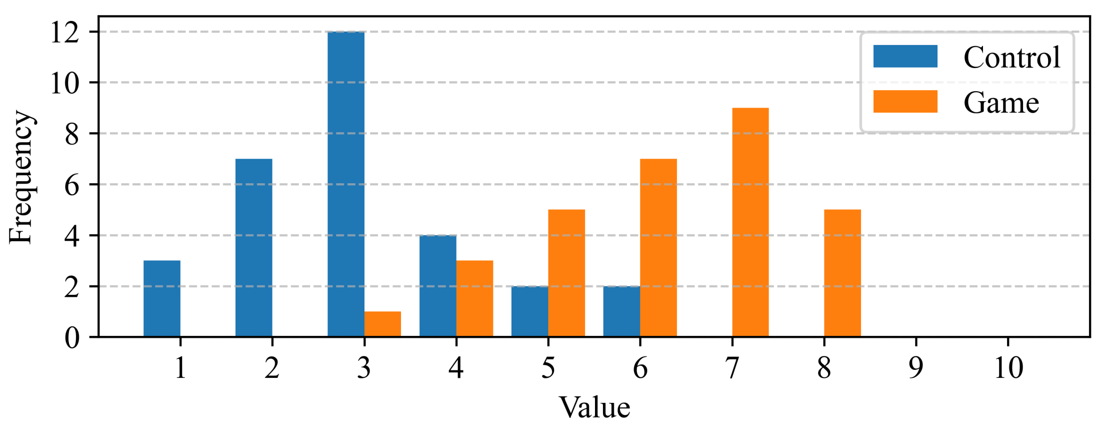
We used two-sample independent t-tests [15] to determine the statistical significance of our findings. Let μ_c be the mean test score of the control group and μ_g be the mean test score of the treatment group. Our null hypothesis is that $\mu_c = \mu_g$ and the alternative hypothesis is that $\mu_c < \mu_g$. With a confidence level of 99%, the calculated t-value is -8.11, and the p-value is less than 0.00001. Thus, we reject the null hypothesis and accept the alternative hypothesis: students exposed to the game show higher test scores than those exposed to the review worksheet. Similar analysis for engagement and confidence reveal statistically significant improvements between the treatment and control groups, with both p-values below 0.00001. The likelihood of these results occurring by chance is approximately zero.



(a) Score (out of 10) on test



(b) Self-reported confidence level (out of 10)



(c) Self-reported engagement level (out of 10)

Figure 5: Distributions of score (a), confidence (b), and engagement (c) for control and treatment groups.

Students with higher test scores also tended to report higher confidence and engagement levels, as shown in Figure 6. However, the correlation was relatively weak. Using bivariate linear regression, we observe a coefficient of determination of 0.61 and 0.45 for predicting test scores with confidence and engagement, respectively. These results align with past research that has found a positive association between student's confidence in their own abilities and their test scores in school, as well as research suggesting students more engaged in the learning process tend to perform better [16, 17, 18].

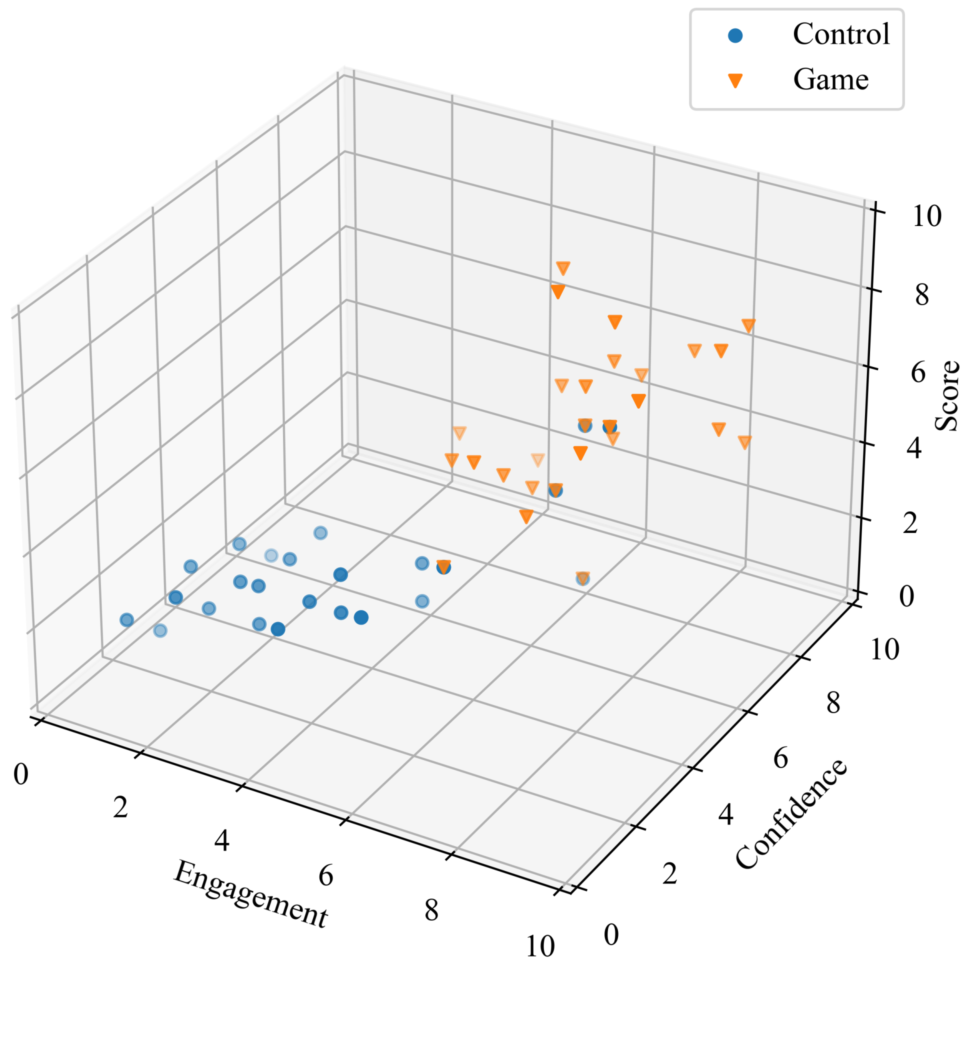


Figure 6: 3D plot of scores, confidence, and engagement of students from the control and treatment groups.

Anecdotal reports from participants also suggested general satisfaction for participants exposed to the game compared to sentiments of boredom for participants exposed to the review worksheet. In addition, some participants exposed to the game agreed with the statement that "they would enjoy more interactive learning methods similar to those in the experiment for similar subject areas." This suggests that interactive learning proved to be more entertaining for students, which confirms previous experiments which found that active learning methods are more engaging. All in all, the relationship between the three variables of tested aptitude, self-reported confidence, and self-reported engagement confirmed previous results in educational research and extends those results to specifically education in digital logic design.

Thus, the findings of this study provide compelling evidence for the efficacy of interactive learning games in the context of teaching Karnaugh maps. The comparison between interactive game-based learning and traditional passive learning yielded significant improvements in three crucial variables: student engagement, confidence, and aptitude.

Discussion

First and foremost, the observed increase in student engagement is particularly noteworthy. Interactive games inherently possess elements that captivate learners' attention, drawing them into the learning process [13]. This engagement is likely a result of the interactive nature of the games, which allows students to actively participate and immerse themselves in the learning material [19]. The gamified learning model provides the opportunity for competitiveness in learning, which has been shown to improve educational outcomes and extrinsic motivation for students [14].

Furthermore, the boost in student confidence following interactive game-based learning underscores the potential of this approach to empower students in their academic pursuits. Confidence is a fundamental aspect of learning; when students feel more assured in their abilities, they are more inclined to tackle challenges and persist in the face of obstacles [16, 17]. Past research has shown a two-way causal relationship between self-confidence and learning aptitude [18]. In other words, improving a student's self confidence oftentimes improves their learning outcomes, and vice versa. The interactive nature of the game likely contributes to this increase in confidence by providing students with immediate feedback and opportunities for trial and error in a low-stakes environment [20]. Compared to a review worksheet and other passive learning methods, there are significantly more opportunities to immediately understand a student's own potential areas of improvement. Such immediate feedback has shown to provide opportunities for greater academic growth for students and forms an important backbone for active learning methods [20].

Perhaps most compellingly, the observed improvement in student aptitude highlights the educational value of interactive learning games in facilitating deeper understanding and mastery of complex concepts such as Karnaugh map-based SOP minimization. Traditional passive learning methods often rely heavily on rote memorization and passive absorption of information, which may limit students' ability to truly comprehend and apply the material [21]. In contrast, interactive games offer a dynamic and interactive platform for students to actively engage with the content, fostering critical thinking skills and conceptual understanding. The significantly higher objective test scores for participants exposed to game-based learning suggests that the hypothesis that interactive learning methods may be better suited for improving student understanding in digital logic design. By providing students with opportunities to explore and manipulate Karnaugh maps in a hands-on manner, these games enable a more immersive and experiential learning experience, ultimately leading to greater proficiency in the subject matter.

Conclusion

This study can be improved in several different ways. The limited sample size of participants exposed to game-based learning and of participants exposed to passive learning methods reduces the utility of the experiment's results. For future experiments, it would be suggested to increase the number of participants to minimize margin of error. In addition, this paper focused on a small area within digital logic design (that of Karnaugh map-based SOP minimization), but future research would serve well to broaden the scope of its experiments to include more advanced topics and unveil whether the results of this paper can be applied to broader conclusions within digital logic design education.

Some potential improvements and suggestions for future research include expanding such gamified approaches to other logic structures such as ESOP (Exclusive-Or Sum-of-Products). In addition, other possible improvements include expanding the game to include more than two players and including time constraints. In many standardized testing situations, students are required to intuitively minimize Karnaugh maps into Sum-of-Products, which would be better trained via time constraints for the game. Such time constraints would also add to the competitive nature and gamify the approach more, which may result in more engagement than in its current iteration. More players would also increase the complexity by several levels and encourage even more long-term thinking and complex moves, especially in Karnaugh maps with more variables and possibilities. Another possible area to explore is whether initial passive learning, which both groups exposed to the worksheet and groups exposed to the game experienced via the review video, actually does boost active learning. Past research has shown that "passive-first learners" tend to perform better than "active-first learners"; this means that it is possible that traditional education methods such as lectures and textbooks are still required for interactive learning methods like game-based approaches to be effective [22].

In conclusion, the results of this study provide compelling support for the integration of interactive learning games into educational settings for teaching Karnaugh maps. By enhancing student engagement, confidence, and aptitude, interactive games offer a promising avenue for educators seeking to enrich the learning experience and empower students in their academic endeavors.

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Appendix A EXPERIMENTAL DATA

Table 1: Test scores, self-reported confidence and self-reported engagement for participants exposed to the review worksheet.

	Score	Confidence	Engagement
Participant 1	4	6	3
Participant 2	3	4	1
Participant 3	2	5	4
Participant 4	5	7	5
Participant 5	6	7	6
Participant 6	2	4	3
Participant 7	3	5	2
Participant 8	7	8	5
Participant 9	2	7	6
Participant 10	3	5	2
Participant 11	3	3	3
Participant 12	3	4	3
Participant 13	2	2	3
Participant 14	3	5	4
Participant 15	4	6	3
Participant 16	2	4	3
Participant 17	3	3	2
Participant 18	2	2	4
Participant 19	3	4	2
Participant 20	2	1	3
Participant 21	2	3	2
Participant 22	2	2	2
Participant 23	3	4	3
Participant 24	3	2	3
Participant 25	2	1	3
Participant 26	1	1	2
Participant 27	3	2	1
Participant 28	2	2	3
Participant 29	3	3	4
Participant 30	2	1	1

Table 2: Test scores, self-reported confidence and self-reported engagement for participants exposed to the game.

	Test Scores	Confidence	Engagement
Participant 31	5	7	4
Participant 32	5	5	5
Participant 33	6	6	4
Participant 34	5	7	7
Participant 35	7	8	6
Participant 36	5	6	5
Participant 37	8	9	8
Participant 38	4	6	3
Participant 39	4	4	7
Participant 40	6	6	7
Participant 41	7	8	8
Participant 42	8	7	7
Participant 43	6	7	8
Participant 44	7	7	7
Participant 45	4	6	6
Participant 46	8	9	7
Participant 47	3	5	8
Participant 48	9	6	7
Participant 49	5	9	8
Participant 50	7	8	5
Participant 51	7	8	6
Participant 52	2	7	6
Participant 53	8	7	7
Participant 54	6	7	6
Participant 55	7	8	6
Participant 56	5	7	5
Participant 57	6	9	7
Participant 58	7	8	4
Participant 59	10	7	5
Participant 60	7	7	6