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Original Paper

Solving Electrical Engineering Puzzles Using Spatial Reasoning

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Abstract

The precursor of any problem-solving strategy is the visualization of the problem at hand. When dealing with problems pertaining to STEM (science, technology, engineering, and mathematics) areas, visualization plays a very significant role in addressing the same. Several initiatives are being taken to improve the visualization skills of the students and spatial reasoning techniques have proved to be one of the most widely accepted tools for addressing the problems in the STEM field. In this paper, we specifically address the use of spatial reasoning to solve problems in the form of puzzles taken from electrical engineering and analyze the fruitfulness of employing such a strategy. The puzzles are hosted in an online interactive framework called UNTANGLED and classified into different categories on the basis of the nature of the puzzles and their difficulties. The results indicate that spatial reasoning technique indeed helped the players to successfully complete the puzzles. The interpretation of the data led to the conclusion that spatial reasoning techniques are imperative when it comes to discerning and resolving a problem, especially in the STEM domain.

Keywords

STEM, spatial reasoning, UNTANGLED

1. Introduction

Educating learners, young and old, in the STEM (science, technology, engineering, and mathematics) fields found a basis in the academic threat to the United States by the Soviet Union launch of Sputnik in 1957, which lead to the creation of NASA in 1958, authorized by President Eisenhower. NASA was further supported by President Kennedy, resulting in more advances that placed a man on the moon.

Subsequent to these efforts, the cell phone, space shuttles, personal computers, and other technological advances, culminating, in the 1990's the establishment of National Science Education Standards, the National Council of the Teachers of Mathematics, lending credence to standards for teaching and learning science and mathematics. The National Science Foundation coined the term SMET for the compilation of the four content areas, then changed it to STEM in 2001 (Fox, 2018).

The turn of the 21st century ushered in an urgency to increase students' proficiency in the STEM areas, which was highlighted in a report, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future* (National Academy of Sciences, 2007). The findings prompted President Obama to promote the *Educate to Innovate Initiative* in 2009, which resulted in funding for 100,000 STEM teachers, to be employed by 2021. The National Academy of Engineering noted in 2015 that the initiative had begun to make progress toward the employment level and had included engagement with industry to promote STEM learning (Engineering, 2015). While these are important milestones in progress toward engaging students STEM learning in schools, the support for these fields remain primarily in the areas of mathematics and science (Education, 2018).

Although knowledge and skills in mathematics and science are important to learning for engineers, the additional need to support and promote spatial reasoning is equally valuable (Basson, 2002; Black, 2005; Casey, 2008; Wai, 2009). In spite of the need, an examination of teaching spatial reasoning remains outside the realm of teaching and learning in STEM fields (Pillay, 1998; Uttal, Meadow, Tipton, Hand, Alden, Warren, & Newcombe, 2013; Wai, 2009). More recently, a group of scholars demonstrated meaningful approaches to training students in spatial reasoning, with positive results (Ardebili, 2006; Contero, 2012; Ha, 2017; Hsi, Linn, & Bell, 2013; Lin, 2014; Martin-Dorta, 2011; Pedrosa, 2014; Samsudin, 2011; Uttal & Cohen, 2012). Methods used included virtual manipulatives, gaming, mixtures of physical and virtual manipulatives, all resulting in increased spatial reasoning among engineering students and STEM high school students.

The purpose of this study was to examine the spatial reasoning used by participants in a series of virtual puzzles designed to engage in the process of solving electrical engineering problems. Although the population that completed the puzzles is unknown, the results of a priori data suggest a need for spatial reasoning to successfully complete the puzzles, verifying the need for spatial reasoning inherent in electrical engineering.

2. UNTANGLED—The Online Framework

2.1 Background

The puzzles, as discussed in the previous section are hosted in a crowdsourced, online interactive game-like design framework to solve mapping/placement problem for custom reconfigurable architectures called UNTANGLED (https://www.untangled.unt.edu) (Mehta, Crawford, Luo, Parde, Patel, Rodgers, Sistla, Yadav, & Reisner, 2013). The objective of this game is to bring in human intelligence and human mapping strategies for mapping data flow graphs onto a Coarse-Grained

Reconfigurable Architectures (CGRAs). In this game, players are presented with dataflow graphs in the form of puzzles taken from applications in the domain of signal and image processing. While playing puzzles, players arrange the nodes of a dataflow graph in a dynamic workspace on the basis of some underlying architecture specific constraints. The puzzles contain a bunch of interconnected nodes but in terms of designer's perspective, these are different computational components such as ALUs, multipliers, etc.

2.2 Gaming Environment

UNTANGLED gaming environment provides the player with the option to choose puzzles that conforms to different architectural styles. There are in total thirteen different architectural styles (see Figure 1). Each of the different architectures contains a dedicated tutorial section followed by the different set of puzzles on the basis of an increased order of difficulties. For example, the players are presented with different puzzles for the stripe architecture (see Figure 2).

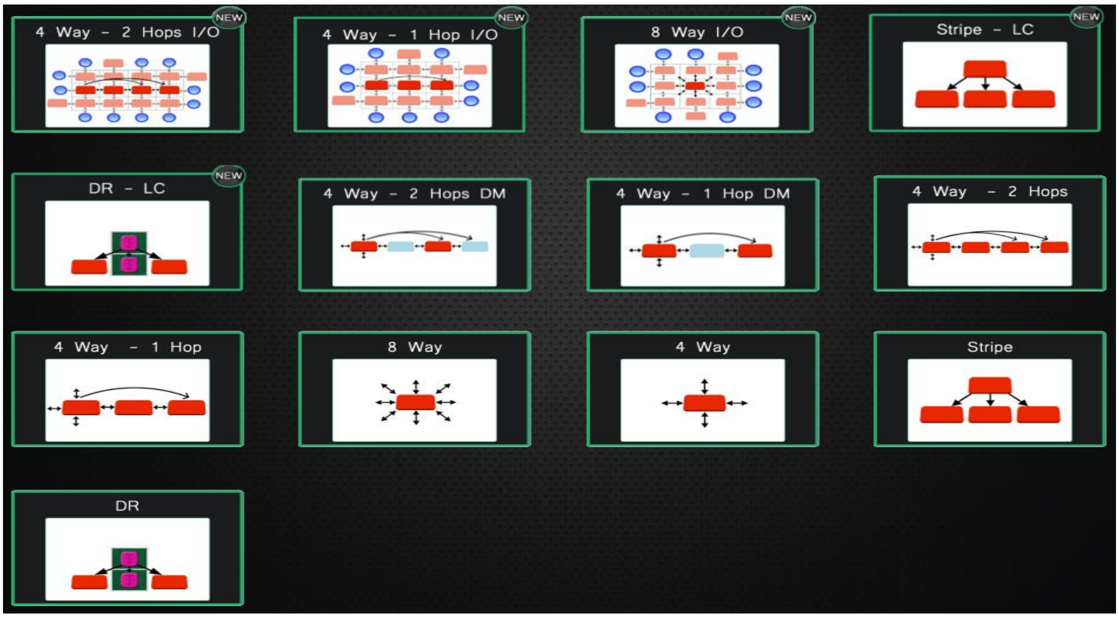

Figure 1. Different Architectural Styles in the Game UNTANGLED

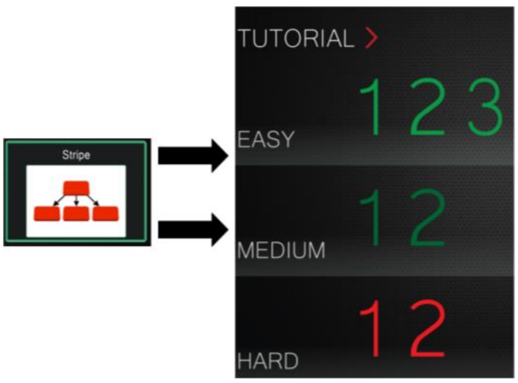

Figure 2. Order of Difficulty in the Stripe Architecture

2.3 Stripe Architectures and the Constraints

The analysis presented in the paper deals with the stripe architecture. The term architecture, in the context of UNTANGLED, refers to a layout of the nodes represented in the data flow graphs in a given dynamic workspace and the way they are connected. When looked from the perspective of a CGRA the nodes are the place where the computational elements are placed. Stripe architecture possesses a specific characteristic feature called crossbar to interconnect. This means that the computational elements in the data flow graph are placed in a row and all of them in the given row are connected to the computational elements that are in the adjacent row. Such an architecture signifies the data flows from the top to the bottom uniformly. The red blocks represent the computational elements and the arrows indicate the direction of data flow, i.e., top to bottom (see Figure 3).

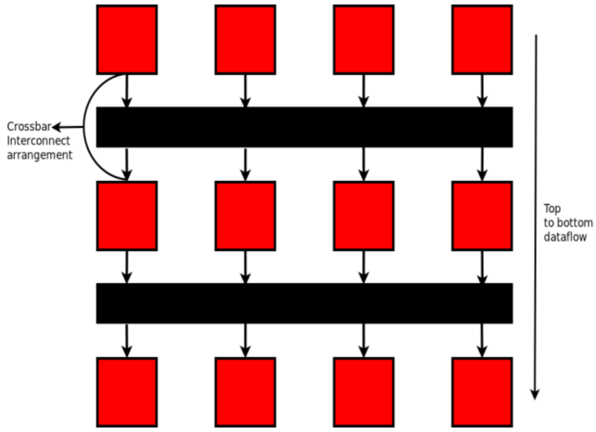

Figure 3. Stripe Architecture

In the game UNTANGLED, the stripe architecture is categorized into seven levels on the basis of gameplay difficulties (see Table 1). Each of the seven levels from an electrical engineering perspective represents seven different benchmarks from the MediaBench suite. The seven benchmarks chosen for our study are Sobel (E1) and Laplace (E2) edge detection benchmarks, as well as GSM (E3), ADPCM decoder (M1), ADPCM encoder (M2), IDCT row (H1), and IDCT col (H2).

Table 1. Various Levels in the Stripe Architecture

Sl. No.	Levels	Nodes	Edges
1	E1 - Easy Level - 1	24	29
2	E2 - Easy Level - 2	29	29
3	E3 - Easy Level - 3	29	34
4	M1 - Medium Level - 1	29	36
5	M2 - Medium Level - 2	36	53
6	H1 - Hard Level - 1	52	63
7	H2 - Hard Level - 2	62	72

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The measure of the difficulty of the levels is the number of nodes and the edges the dataflow graphs in the level comprises of. Higher numbers suggest denser graphs with a lot of interconnections, with the simplest graphs being easy to lay out in a readable manner and the hardest graphs quite difficult.

3. Data Analysis

The data from the stripe architecture were sorted into various categories, plotted, and analyzed. The description of the findings is discussed below with adequate texts bolstered with their respective plots.

3.1 Findings

3.1.1 Choice of Moves across Different Levels in the Stripe Architecture

The moves performed by the players from all the levels of the stripe architecture were considered to analyze what kinds of moves the players primarily resorted to. The moves have been classified into six categories: single, multi, swap, add pass gates, remove pass gates and finally rotate. In case of a single move, a node is moved from one location of the gaming workspace to another location without affecting the position of any other nodes. The multi-move is an extension of the single move wherein, instead of a single node, a group of nodes is selected at a time and dragged from an initial position in the gaming workspace to another position. The swap takes into account a single node or a group of nodes and when dragged on top of another node or a group of nodes respectively, exchanges the position in the gaming workspace. Players can introduce a special kind of node for the purpose of meeting the architectural constraints during their gameplay. These special nodes are called pass gates. They are used to route data from one node to another and has to be thoughtfully introduced in the game as they require extra energy to perform their operation. A player can easily remove a pass gate from the game when it will be deemed as a remove pass gate move. Rotate moves provide a flexibility to the player to select a group of nodes and rotate them either clockwise or anticlockwise and help them to fit those nodes in the gaming workspace and reduce the number of violations.

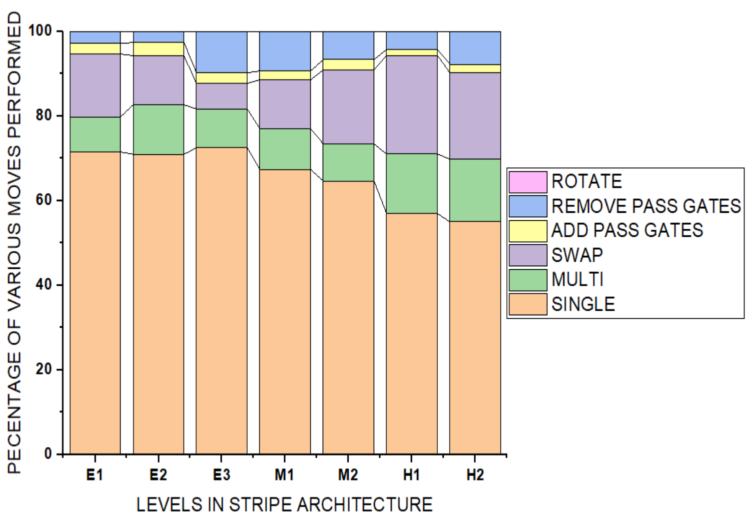

Figure 4. Percentage of the Moves Performed across All Levels in the Stripe Architecture

The x-axis represents the various levels of the stripe architecture and the y-axis represents the percentage of different kinds of moves performed by the player (see Figure 4). The trends observed are extremely parallel for each of the moves across all levels. Players have found single move to be the most useful among all the six different move types irrespective of the level. However, an interesting observation to point out is that the percentage of single moves performed by the players diminished as the difficulty of the levels increased. For instance, the percentage of single moves dropped to 55% in the H2 level from 72% in the E1 level. This indicates that the players felt the need to resort more towards the other move types in order to find a feasible solution to the game. Almost all the different moves were being performed by the players in all the levels of the stripe architecture except for rotation. Multi moves percentage also witnessed an increase as the players played higher levels, suggesting the fact that increased complexity in the levels encouraged players to deal with multiple nodes at a given time. Higher complexity on the levels also compelled the players to perform a lot of swap moves. The highest difficulty levels had a lot of swap moves in the range of 20% to 30%, while in the easier levels the number ranges from 10% to 15%. It is also observed that players had to perform more number of remove pass gates moves in the higher difficulty levels as they felt the need to remove them can yield a better solution to the games in the level.

3.1.2 Choice of Moves among Different Gameplay Patterns

In order to keenly observe the trends in the moves performed, the players are grouped into the following categories:

- E1
- E2
- E3
- M1
- H1
- H2
- M1 & M2
- H1 & H2
- E1 & H2
- EASY
- ALL

The itemized groups represent players who played only those groups. EASY represents all those players who played all the easy levels only while ALL represents players who played all the levels. No cases were found for only M2. The magnitude of the number of moves performed across the levels are scaled down to the percentage scale and column plots are provided to interpret the data. Due to the consistency of patterns, no further higher-level analyses were conducted.

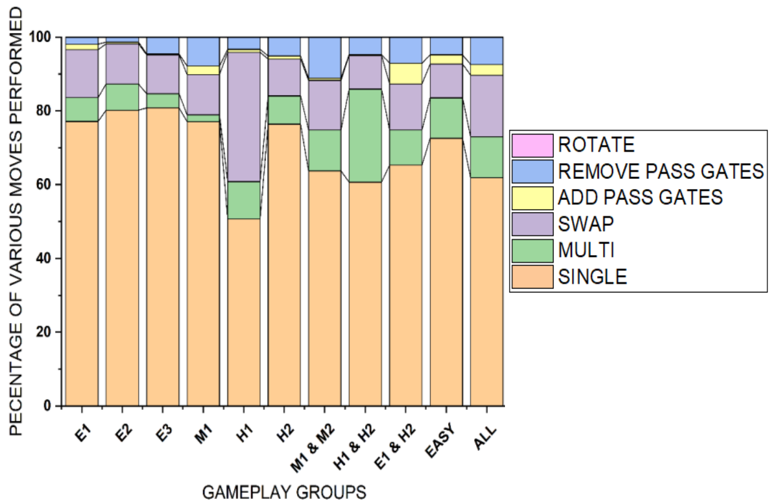

Figure 5. Percentage of the Moves Performed across All the different gameplay groups in the Stripe Architecture

The plot (see Figure 5) represents the categorical gameplay groups of the participants. The x-axis represents the players who played only the marked levels. This plot reveals the trend of using single moves by all participant categories and hence bolsters the previous findings. As the difficulty level increased the choice of using the single moves prevailed but at the same time other moves were also being performed. When the moves for the highest difficulty levels, i.e., H1 and H2 were combined, it became very much evident that multi moves seemed a feasible move type for the players. The percentage of moves performed in total for H1 & H2 is around 25% while the same for all the other groups fell in the range of 4% to 11%. The percentage of swap moves in H2 were higher when compared to the same in other groups which highlight that difficult levels encouraged players to perform a lot of swap moves to arrange the nodes. As an inference, this means that for graphs that have more number of nodes and edges, players have used multi moves and swap moves to deal with the many nodes in the gaming workspace at a given time.

3.1.3 Variation of Scaled Average Score across Different Gameplay Groups

The plot (see Figure 6) shows the scaled average scores across different gameplay groups in the y-axis and the x-axis represents the players who played only the marked levels. The scoring function is formulated in such a way that the objective of the player should be to maximize the numerical value of the function. The scoring function takes into account the power, the area consumed by the computational elements in the gaming workspace and the performance. Lesser the power consumed, higher will be the score. In terms of area, the objective of the player should be to fit the computational elements in the gaming workspace in such a way that the least number of rows and columns are utilized to accommodate them. The score is thus dependent on the level that is being played. For example, the easy levels will have a base score which is always lesser than the base scores of the more difficult levels. This results on account of the increase in complexity of the graph in terms of the number of nodes, edges, and interconnections. To mitigate this problem and to bring uniformity in the analysis, the scores of all the levels are scaled by dividing the actual score with the number of nodes and edges in the graph (see Table 1). This gives a score on per node and per edge basis. Once this scaled score is obtained, the average is being calculated to find out the average trend across different gameplay groups.

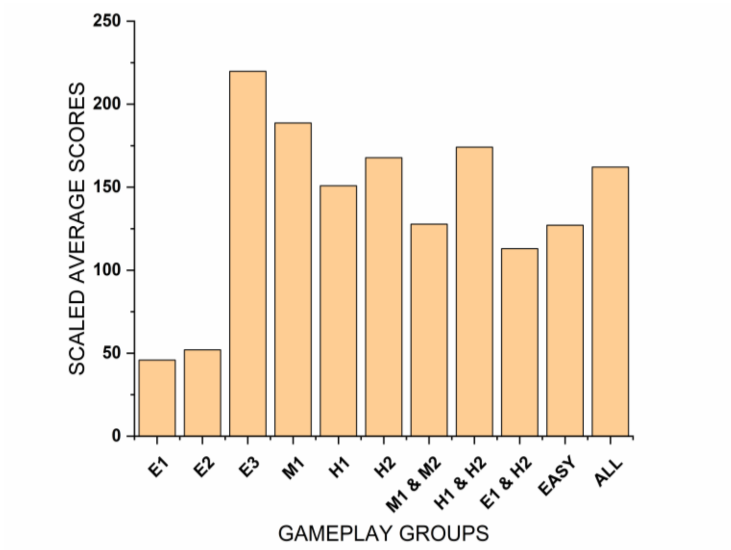

Figure 6. Scaled Average Scores across Different Gameplay Groups

This plot shows that the highest scaled average score was among participants who chose to solve the E3 level of the stripe architecture. It is also observed that the average scaled score seemed to be on the higher side as the difficulties increased. The easier two levels witnessed very low scaled average score. For example, the scaled average score for the players who played E1 or E2 was in the range 40 to 50. While the players who played E3, M1, H1 and H2 had a much higher scaled average score. This gives an inference that players are able to deal with more complex graphs even though they did not gain much experience by playing the easier levels.

3.1.4 Chain Analysis

The stripe architecture, as discussed before contains rows of computational elements that are connected to the computational elements in the immediately adjacent rows. As a consequence, it is found that players who possess spatial visualization skills are able to arrange these computational elements in the form of vertical chains. A chain is a form of arrangement where one computational node is connected to another computational node that is placed directly beneath it (see Figure 7). The computational elements that are colored green forms a chain while those that are not green do not form a chain. The pink colored nodes represent a pass gate and their presence is not taken into consideration to determine the chain. For instance, the computational nodes that are labeled 43, 47, 49, 52, and 53 form a vertical chain of length 5. The computational elements that are labeled 38 and 44 forms a vertical chain of length 2. In this case, we cannot consider the pass gates labeled 9033 and 9025 in the chain with the computational elements 38 and 44 even though they are connected vertically in the same column because they are pass gates.

The data collected from the gameplay data of the stripe architecture reveals that players were, in fact, able to utilize their spatial visualization techniques and come up with their own vertical chains. The number of observable chains that are being identified by greater than or equal to two players in the level is found to be increasing as the difficulty of the levels increase. This means greater the number of nodes and edges in a given level, greater is the probability of creation of a vertical chain (see Table 2). It is interesting to note that the increase in the number of nodes and edges in a given level, however, does not influence the average chain length. Spatial visualization technique is thus helpful in determining the number of chains but not its length.

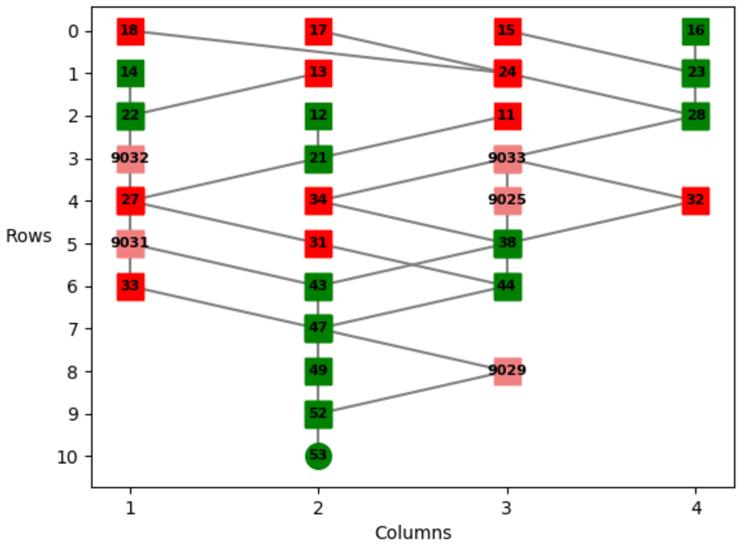

Figure 7. Representation of Chains in Stripe Architecture

Table 2. Number of Chains in Different Levels of the Stripe Architecture

Levels	Number of Chains	Average Chain Length
E1	62	4
E2	32	4
E3	38	6
M1	22	5
M2	65	4
H1	100	5
H2	123	5

In this subsection of the analysis the levels E1, M2, and H2 are considered as they had more number of chains in the easy, medium and hard groups respectively and for better readability of the plots, top twenty players were considered.

The initial graphs that were presented to the players (see Figure 8, Figure 11 and Figure 14) had computational elements dispersed all throughout the gaming workspace. It is also evident that as the difficulty level increases the number of pink colored blocks i.e. the pass gates increases in number too. The final solutions of the top players in the respective levels (see Figure 9, Figure 12 and Figure 15) strikingly has lesser number of pass gates than the initial graph. Thus, it becomes very much evident that among the top players there is a tendency to reduce the number of pass gates and attain a solution with the least number of pass gates. It is also observed that in E1, the chain with the highest length was identified by fourteen players (see Figure 10) out of the top twenty players. Such a trend was however not observed for M2 and H2 (see Figure 13 and Figure 16).

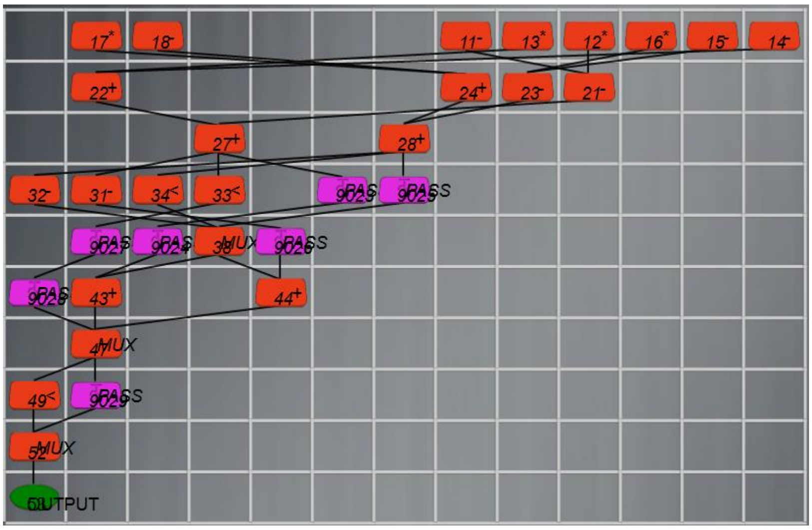

Figure 8. Initial Graph of E1 Level

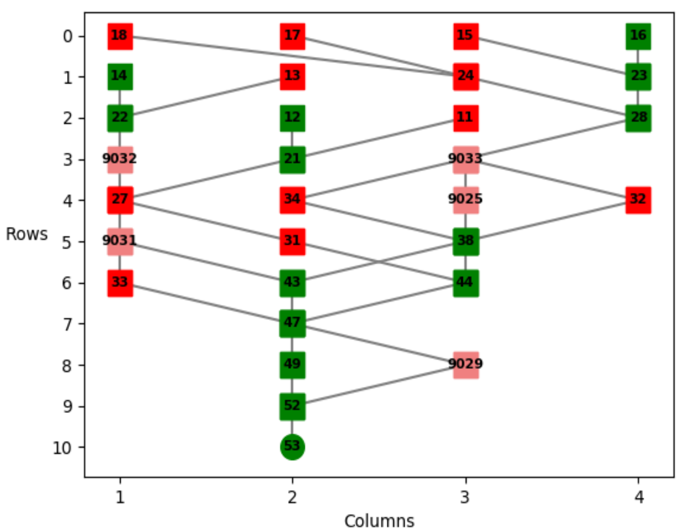

Figure 9. Final Solution of the Top Player in E1 Level

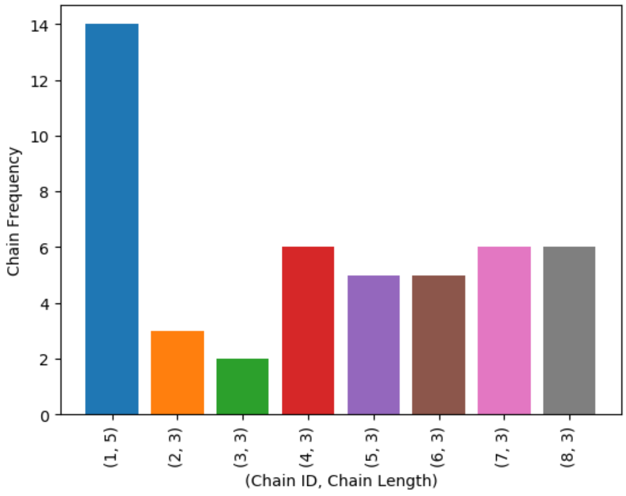

Figure 10. Number of Players Determining the Chain and the Chain Length for E1 Level

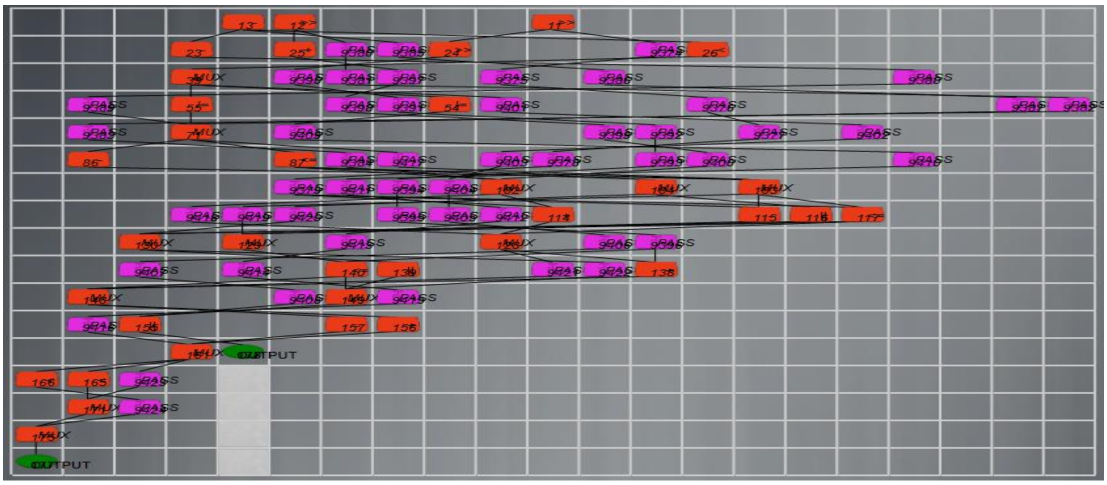

Figure 11. Initial Graph of M2 Level

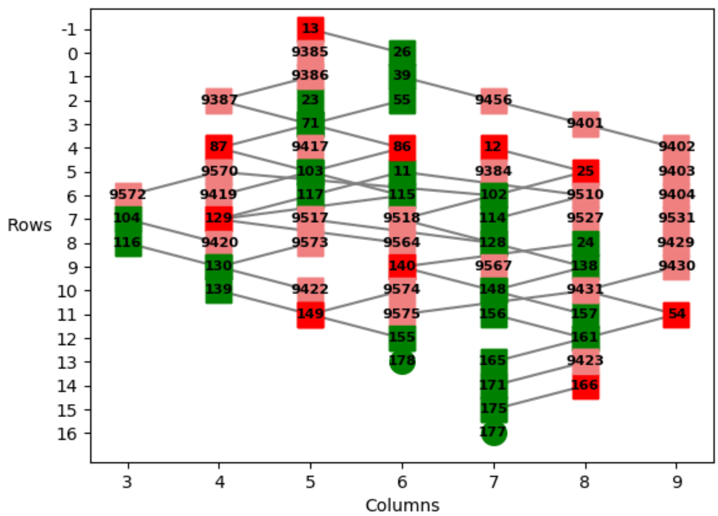

Figure 12. Final Solution of the Top Player in M2 Level

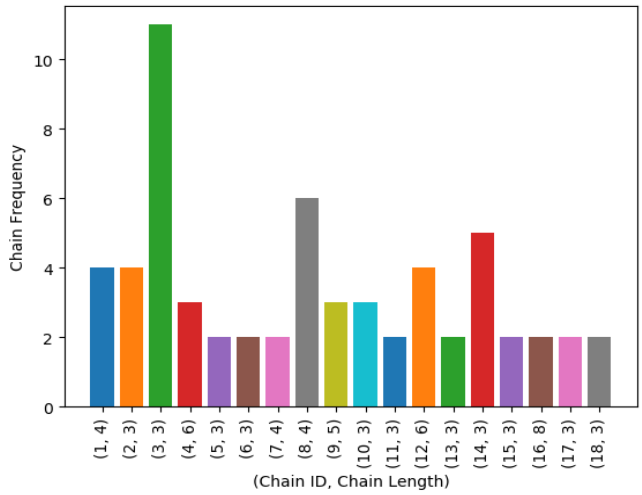

Figure 13. Number of Players Determining the Chain and the Chain Length for M2 Level

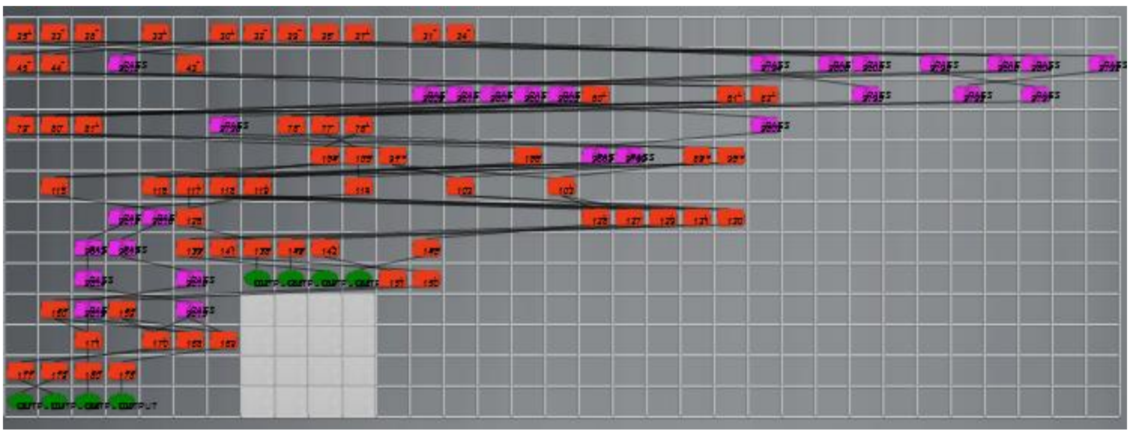

Figure 14. Initial Graph of H2 Level

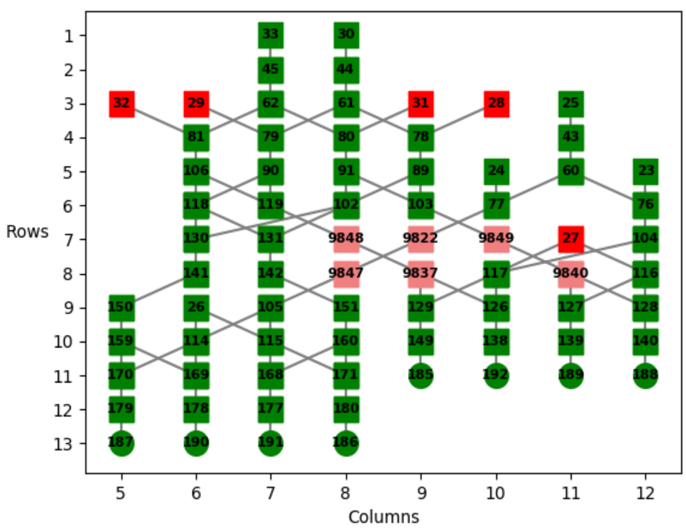

Figure 15. Final Solution of the Top Player in H2 Level

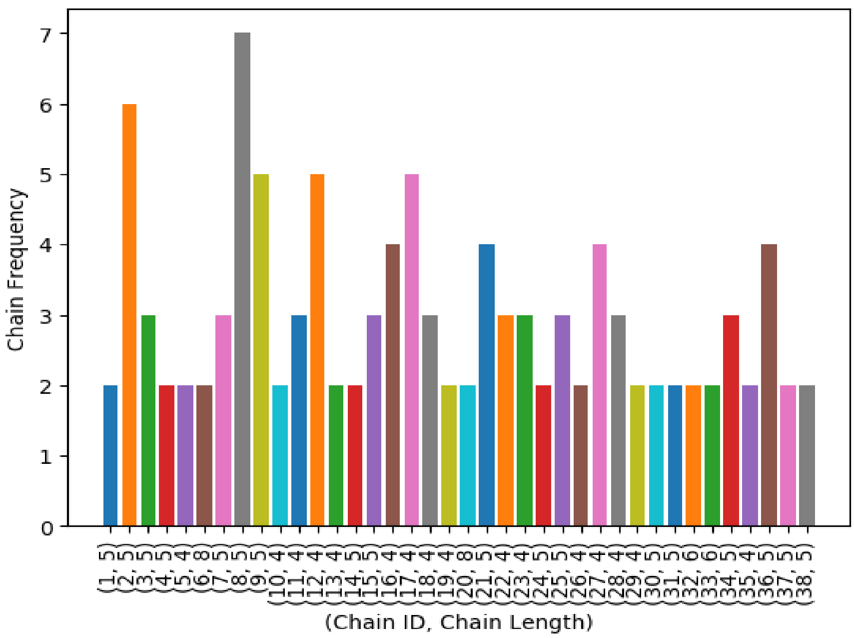

Figure 16. Number of Players Determining the Chain and the Chain Length for H2 Level

4. Recommendation

In order to develop engineers for the future needs of the country and the world, educational settings, including engineering schools in universities and colleges will need to foster the development of knowledge and skills in the area of spatial reasoning. One approach is the Innovative Virtual and Physical Manipulative (VPM) wherein students both touch and visualize the movement of objects in hands and virtual space (Ha, 2017). The study of this innovation found that students in engineering courses increased student learning in spatial reasoning and engineering problem-solving. In addition, students reported a preference for learning by the VPM method over the use of physical or virtual methods individually. By teaching students spatial reasoning in undergraduate engineering courses, researchers found that increasing spatial reasoning skills served as a predictor for success courses and assisted in the approaches students employed when approaching engineering problems (Hsi, Linn, & Bell, 1997). The practice of intentionally teaching and fostering spatial reasoning among engineering students is vital to the successful development of engineering within the STEM field. These studies provide models for replication in university engineering programs as well as STEM programs in all levels of education.

The use of puzzles, similar to the one examined in this study, for encouraging students to test spatial reasoning is a starting point. However, it would be valuable to study how the participants make decisions to solve the puzzles, thus provide designers and educators with ways to use the puzzles to encourage and develop spatial reasoning among learners with an aptitude for engineering. In addition, puzzles could be used to assess students' competence in spatial reasoning, setting the trajectory for designing instruction that intentionally promotes and supports spatial reasoning. Finally, spatial reasoning needs to be supported in educational circles, as well as game development arenas. Game developers and educators in

STEM fields must find common ground to develop the intentional tools necessary to both develop and test the efficacy of students' learning of spatial reasoning necessary for engineering.

5. Conclusion

In general, the trends of moves and scores revealed that the higher the level, the higher the score, and the greater the number of moves used to solve the puzzles. In essence, due to the various challenges of higher level puzzles, participants required more moves to come to a solution. In addition, but making more moves, no matter the type, more points were accumulated. In order to succeed in solving the puzzles, the spatial reasoning was imperative. The configuration of the parent-child, unidirectional, vertical relationship, forced the participants in the puzzle solving to use spatial reasoning to come to a successful conclusion of the game.

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