DIGITAL GAME-BASED LEARNING FOR TEACHING BOOLEAN LOGIC GATES TO KS4 COMPUTER SCIENCE PUPILS

Phillip Benachour, Alex Phillips

Lancaster University (UNITED KINGDOM)

Abstract

Game-based learning has transformed learning for children and adults alike and has been applied to formal, informal settings and professional training too. Though games are not the only way to improve learning and engagement, there exists substantial literature on pedagogical approaches, research methods, and evaluation techniques for learning with games. The aim of this research is to explore how the use of game design principles and mechanics can be effectively integrated with curriculum requirements to augment student learning and subject engagement beyond the classroom. The curriculum of interest here is logic gates and their operations as part of Key Stage 4 of the Computer Science curriculum in England. The age range at KS4 is 14–16-year-olds. The goal of the game is to help students understand simple Boolean logic, for example: AND, OR and NOT, and apply it to logic gate circuits.

The game is divided into different levels of difficulty to enable participation and attempts at problem-solving for students with mixed abilities. The game application was designed with three specific learning objectives: (1) Produce a logic circuit to solve a given problem or to implement a given written logic statement. (2) Recognize and use standard symbols to represent logic gates. (3) Produce truth tables for given logic circuits. The proposed application uses puzzle design in the game's mechanics across three different categories where problem-solving grows with complexity: easy, medium and challenging. It utilizes eight different puzzle design principles to enable scaffolding whilst learning. The complexity between the categories is defined by the number of gates required where easy levels have between one and three gates, medium levels between four and five gates, and challenging levels six+ gates.

A pilot user study was conducted to evaluate the game's effectiveness and impact. A survey was designed to collect qualitative surveyed data on player motivation, game play quality, subject understanding, and user satisfaction. Participants were selected based on a range of technical abilities, including current Computer Science teachers, previous GCSE (KS4) Computer Science students, and users with no educational Computer Science experience.

The teacher "strongly agreed" that the levels build up in difficulty gradually, the tutorials provided an understanding of what each gate does, understand what the function of each gate is, as well as being able to identify all six gates used. The teacher however, "disagreed" that because of the game they increased their knowledge of logic gates. For the students all users stated the game "improved" their ability to produce a logic circuit to solve a given problem or to implement a given written logic statement. This demonstrates a difference in expectations between students and teachers. All users stated that they would have found this game useful at GCSE level, enjoying the interactive experience. All users would also recommend that GCSE teachers use the application within their curriculums.

Keywords: Game-based learning, problem-solving, scaffolding of learning.

1 INTRODUCTION

Research on educational digital games has previously shown that learner motivation, and engagement with curriculum-based subjects, increases resulting in improvement in student performances. Studies in [1] have shown that the use of educational games to augment learning beyond the classroom enhances players' attention and motivations. Research in [2] showed that students who engaged with game-based learning have a higher level of motivation towards learning which improved their academic performance. Further, it was shown in [3] that students invest more time and energy and tend to be more motivated in areas they have a great interest in. This underpins the idea that interest is categorized as an important factor that influences learner motivation and engagement with a subject.

Game-based learning applications require user engagement to ensure the learning process takes full effect, with game-play time being one of the key factors to motivate task completion, problem solving and the grasping of key concepts [4]. These motivating factors include the integration of in-game reward systems and competition between users during gameplay. The use of reward-based systems within these applications can often be linked to reinforcement learning or achievement rewards, rewarding learners using positive reinforcement throughout the game. Previous studies have also suggested that providing rewards to students in the form of relevant and immediate incentives, leads to a deeper interest in the subject area and can aid intrinsic motivation [5].

Competition within a learning environment has often been used as a method to promote learning motivation and cooperation between student groups within a classroom [6]. This study presented two types of competition, inter-group competition and between-group competition, where groups of students either competed against other groups or individually against other students within their group. The analysis concluded that between-group competition improves information transmission between individuals, but also observed that between-group competition did not lead to a "higher individual performance compared with players facing inter-group competition". Concluding that inter-group competition is best at improving the performance of individuals, whereas between-group competition is best at improving social skills and information transmission. The study in [6] was also utilised in the design process of the proposed game as it considers the improvement of an individual's acquisition of learning (knowledge of logic gates). As a result, the proposed game will encourage inter-group competition between students within a classroom. Further, the introduction of the previously mentioned "star-based system" and the ability to easily access the game online, will enable students to compare scores within classrooms and beyond. Competition has also been evaluated for serious games with students evaluating the effect of competition within game environments on learning [7]. Results and their analysis in [7] showed that by using an educational-based game in a competitive environment, the motivation and post-test scores of learners improve significantly. This reinforces the proposal of encouraging competition within learning to maintain engagement, but also provides evidence that competition directly improves retained knowledge of students.

2 GAME APPLICATION DESIGN

The learning design used for this game is mapped to the General Certificate of Secondary Education logic gates curriculum of the Cambridge Local Examinations Syndicate [8]. The application was developed to meet the following learning objectives:

- Produce a logic circuit to solve a given problem or to implement a given written logic statement.
- Recognise and use the following standard symbols, shown in Fig. 1, used to represent logic gates.
- Produce truth tables for given logic circuits. This objective was not a requirement for student learning. Through the game application produced truth tables, these were printouts to help with subject learning.

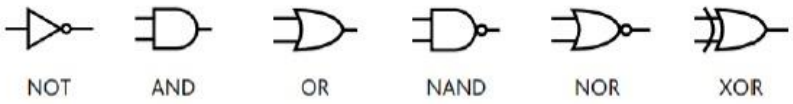

Figure 1. Logic Gate Symbols, taken from [8].

Research and studies in [5] and [7] were utilised in the design process of the game by considering reward-based learning within the level design approach and competition between players as a mechanism to improve learning respectively. The aim here was to ensure students remained engaged and motivated throughout their learning and game-play experience with the implementation of a "star-based system". Fig. 2 shows an example of the game's easy level completion screen with star rewards.

Figure 2. Example of the easy level completion screen with "star" awards.

To maintain a reward-based approach to learning, each level will have three stars to collect, each representing a different challenge and objective acting as an incentive to the player as shown in Table 1 below. The implementation of this reward system ensures that students will be engaged with the application for a set period. A player is rewarded upon completing of a challenge, which is displayed within the main menu for each level (Fig. 3). This provides an additional goal for each player to maximise the collection of stars for every level and complete with other players' scores.

Table 1. Requirements for Obtaining each star reward within each level.

Solution Star	***Optimisation Star***	***Speed Star***
Earnt by completing the level with any solution.	Earnt by completing the level with an optimal solution. Equal to or less than a predefined number of gates.	Earnt by completing the level faster than a predefined time frame.

To ensure the exercises are solvable and reduce cognitive load, the application provides a "hotbar" of gates shown in Fig. 3. This consisted of a row of buttons that will spawn a specific gate, eliminating the need for them to remember the exact symbol for each gate, as well as allowing them to use a drag-and-drop approach when spawning gates into the solution area. This hotbar will consist of all six (NOT, OR, NOR, AND, NAND, XOR) gates used throughout the entire game for all levels, providing consistency for the players. This results in the same process being used for all levels, reducing the barrier to entry and cognitive load.

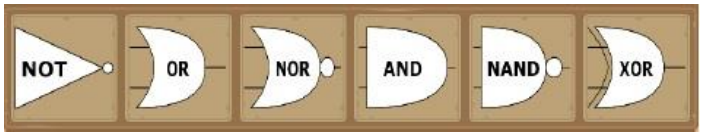

Figure 3. Example of the hotbar with labelled gates.

2.1 Incorporating Puzzle Design as a Mechanic

The game mechanics utilised Schell's puzzle-based design approach shown in Table 2 to give players a sense of progress and reward [9]. The design incorporated these puzzle principles to encourage players to apply problem-solving skills and enhance the game-play learning experience. To ensure that puzzles are designed effectively, Schell identifies several principles of puzzle design to create well-established and effective puzzles. The proposed game incorporated the principles at each level and consisted of a problem statement for the player to solve.

Table 2. In Game Play Puzzle Design Examples.

(1) Make the Goal Easily Understood	***(5) Give a Sense of Progress***
Each of the levels will have a single goal, to illuminate a light bulb, when and only when the problem equation is met (E.g. When light switch A OR light switch B is turned on).	Players will be provided with a sense of progress by collecting stars within the levels for progress within the overall application, collecting rewards for completing each level displayed in the main menu.
(2) Make It Easy to Get Started	***(6) Give a Sense of Solvability***
Each level will have a hotbar, allowing players to simply drag logic gates into the player area. Each puzzle (problem) will start in the same way (dragging certain gates into the solution area).	Players are provided options in the form of possible gates that can be used by dragging them from the hotbar. This allows them to focus on the order of the gates used, providing a sense of solvability and reduce cognitive load.
(3) Increase Difficulty Gradually	***(7) Parallelism Lets the Player Rest***
The application will have a series of problems to solve, each increasing in difficulty from the last and promote scaffolded learning.	Players will be able to stop the attempt of a problem and return at any time. This time-pause period can be used to either attempt a different problem or take a break.
(4) ***Pyramid Structure Extends Interest***	***(8) Give the Answer!***
The problem statement will be broken down in smaller chunks using brackets in the question, prompting the user to attempt the question one part at a time.	When a player submits the correct answer, a win Screen will be displayed indicating that the answer was correct along with some additional information on the completeness of the solution.

As an example, with puzzle principle (2) in Table 2, the hotbar is used to control the difficulty and aid with recall and recognition. For example, within the tutorial and easy levels shown in Fig.4, the hotbar not only shows the shape of each gate, but also their name; further aiding users when trying to understand the function of each gate, but also making the task easier to solve.

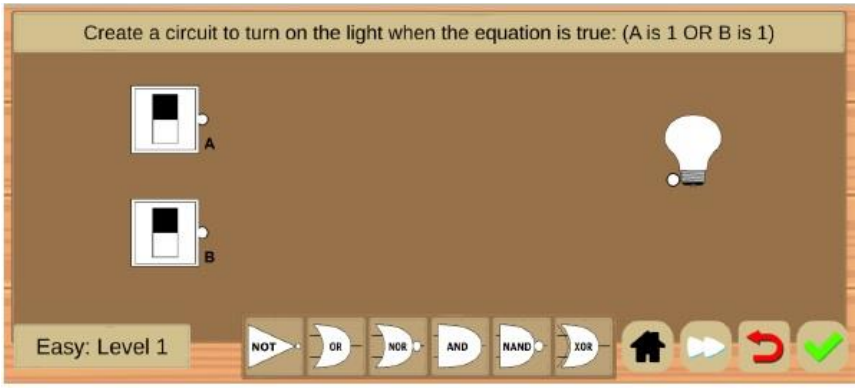

Figure 4. Example of the Easy Level 1 on first initial load.

When the user advances to the medium and harder levels, the labelled gates are removed (see Fig. 5), and players are required to distinguish the gates solely by their shape: Puzzle principle (3). The medium and hard levels remain virtually identical from the easy levels, but the labels on the hotbar switches are removed to encourage users to problem solve by identifying and recognising logic shapes with the appropriate gate name.

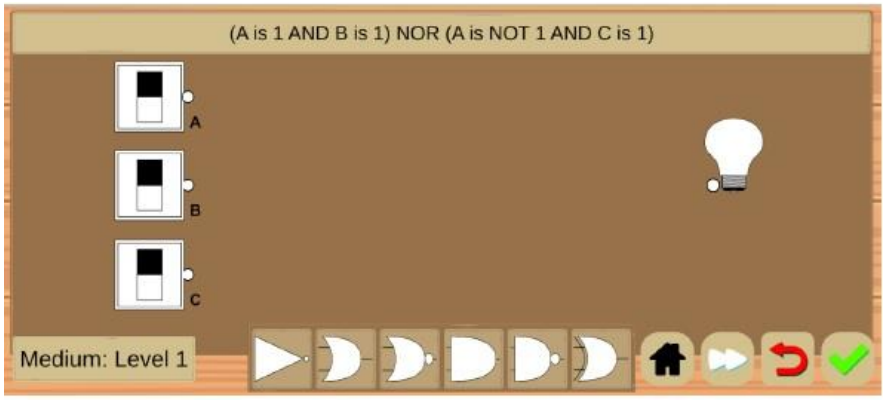

Figure 5. Example of a Medium Level 2.

3 METHODOLOGY

A pilot user study was conducted to evaluate the effectiveness of the educational game with specific focus on learnability, engagement, usability, and gameplay experience. Participants were selected based on a wide range of experience and technical abilities, including current Computer Science teachers, GCSE-KS3 (14–16-year-olds) Computer Science students with prior experience of the subject with varying abilities. This ensures that feedback on the game application receives a wider set of participants with varying levels of computing knowledge and experience. Further, it helps us to appreciate the application's accessibility for students who have less experience of the topic to evaluate learnability. Particular attention will be focused on the Computer Science teachers due to their professional experience around the topic and years of training on working with GCSE students. Participants were asked to play the game beginning with the tutorial levels before advancing to the different "ability" levels and completing as many exercises as possible. It is worth pointing out that only the tutorial levels provide guidance on how to use the application. The assumption here is that a player can refer to the tutorials for extra help and solely focus on problem-solving during game play.

3.1 Qualitative Survey Questionnaire Design

A survey was used to collect qualitative data from all participants. The questionnaire design focussed on three main areas (1) Player engagement and motivation, (2) Usability, (3) Subject knowledge and understand, and (4) Game play quality. Player engagement and motivation relates to the ability of players to complete as many tasks as possible for each level in each category (easy, medium, and hard), as well as storing the stars awarded. As already detailed, the inclusion of the reward system aims to ensure students remained engaged and motivated throughout their learning and game-play experiences.

As different participants completed the study, the results will be split into sections comprising the different groups. These include a GCSE Computer Science teacher and participants with Computer Science experience. The average time taken by each participant to complete the study was 30 minutes.

4 RESULTS AND ANALYSIS

4.1 GCSE Computer Science Teacher

The response from a teacher is shown in Table 3 below. The main point of interest from the teacher's feedback is their encouragement to recommend the game to other teachers currently teaching GCSE logic gates, stating benefits such as the interactive element resulting in time saved due to not having to draw them. Feedback in Table 3 shows that recommendations were made to expand the application such that it provided a mechanism for students to complete. As previously mentioned in the learning objectives truth tables were not a primary objective for student learning.

Overall, the results of the GCSE Computer Science teacher were positive, despite no prior experience of using games for learning. The teacher found it easy to navigate, understand its goals and functions. Additionally, they also suggested that other GCSE students use the application within their studies. Concluding the study, the teacher used the game within a lesson to aid in their teaching practice of GCSE logic gates to students.

Table 3. Responses from Teacher.

Motivation	***Quality***	***Satisfaction***
The introduction of the star system did encourage the attempt of more levels and the reattempt previous levels to earn more stars.	The application was "Easy" to navigate, understand what it was teaching, and figure out the objective of levels.	The teacher either "agreed" or "strongly agreed" that the application was enjoyable, would find interesting if used in a lesson, and helped better understand the topic.
Subject Knowledge and Understanding	***Gameplay***	***Improvements***
The teacher "strongly agreed" that the levels build up in difficulty gradually, the tutorials provided an understanding of what each gate does, understand what the function of each gate is, as well as being able to identify all six gates used. The teacher "disagreed" that because of the game they increased their knowledge of logic gates. The teacher also identified the best part of the game being different levels of difficulty, to stretch and challenge different students.	The teacher enjoyed the interactive experience and recommended that other teachers use the game within their GCSE curriculum. If studying at GCSE level the teacher would have found the game interesting, if used in a lesson, and would have found the game useful.	The teacher suggested "adding in truth tables" in a feature to write the correct Boolean expression given a circuit. Effectively flipping the game around. Additional suggestions also included blank truth tables for the student to fill in.

4.2 Computer Science Students

Results from participants with previous computer science experience are shown in Table 4. This section involves participants who have previously studied GCSE Computer Science. The aim of this section is to evaluate the game from the student's perspective, using participants with knowledge of GCSE logic gates. This also allows for the assessment of the game's ability to refresh students of previously learnt material.

All participants stated that they would have found the game useful if studying at GCSE level again. This highlights the benefits and effectiveness of game-based learning in teaching logic gates, suggesting that the application would prove beneficial to current GCSE students. Additionally, participants suggested the game improved their knowledge and problem-solving skills, enabling them to revisit the topics again. This implies the game could be used as a revision tool, allowing students to remember previously learnt topics.

In relation to design aspects, one participant wrote, "When I did comp sci at GCSE logic gates were a topic which you were expected just to know from looking at them. This game is an interactive way to learn what each gate does, and you can see this visually by creating the circuit and flicking the switch, which is an excellent way to learn this topic".

Table 4. Responses from Computer Science Students.

Motivation	***Quality***	***Satisfaction***
All users reported that the star reward system did increase motivation to complete levels or reattempt previous levels. All users attempted all the levels.	All users stated the application was "easy" or "very easy" to navigate through the application, to understand what the tutorial levels were teaching, and to understand what the objective of each level was.	All users "agreed" or "strongly agreed" that they enjoyed the learning experience, would find it interesting if used in a lesson, and learning through an interactive experience helped better understand the topic.
Subject Knowledge and Understanding	***Gameplay***	***Improvements***
All users "agreed" or "strongly agreed" that they can identify all six gates used in the application along with their functions, the levels build up in difficulty, the tutorial levels give an understanding of what each gate does, and that because of the game they increased their current knowledge of logic gates. Referring to the curriculum, all users stated the game "improved" their ability to produce a logic circuit to solve a given problem or to implement a given written logic statement.	All users stated that they would have found this game useful at GCSE level, enjoying the interactive experience. All users would also recommend that GCSE teachers use the application within their curriculums.	Suggested improvements included expanding the game beyond GCSE to include the A-Level syllabus.

5 CONCLUSIONS

The work presented aimed to develop an interactive digital game-based learning tool to augment the learning and understanding of Boolean logic and apply it to logic gate circuits. Using the proposed game application, the pilot study demonstrated that participants were able to produce logic circuits, solve problems and implement a given written logic statement. All participants agreed that it would be beneficial to use the game within a classroom environment to augment their learning. Further, they stated that the implementation of reward systems improved their motivation, and game play experience.

As a pilot study, this research is limited in terms of participant numbers and would benefit from being evaluated by a larger cohort size. The game would also benefit from being deployed to schools to enable teachers and students to experience the game as learning tool to support classroom teaching.

Additionally, the game doesn't currently contain any sounds, or backing tracks. Although sounds for this game were not in the aims or design, it would provide another element of interest for users from a game experience viewpoint. To achieve this an appropriate music theme would have to be selected and created for scenes such as the main menu as well as snapping sounds for connecting wires to gates.

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