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Development and Evaluation of an Educational Game to Practice the Truth Tables of Logic

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*Abstract***— Already for years, the logic course in the first year of our Bachelor program in Computer Science has been a serious stumbling block for many students. They find the formal and abstract mechanisms of logic difficult and awkward to deal with. Many procrastinate, which results in poor understanding of the basic principles, which in turn causes them to fall even more behind. Previous attempts to remedy this have had little effect. Since educational games are deemed as an enjoyable way to foster learning, we decided to develop an educational game for the course. The game is a two-player competitive game inspired by an existing card game. We adapted this card game to proposition logic and digitized it as an app. The development was done in an iterative way. Each version was evaluated and based on the received feedback the software was improved and reevaluated. Based on the results of the evaluations we can conclude that the game is well suited for its target audience and is a good complement, and even replacement for some of the traditional face-to-face exercise sessions. However, we also noticed that making the game available without obligation to use was not the best approach. A good embedding into the course is needed to ensure that all students use the game. In this paper we present the game, explain and motivate its evolution, and present lessons learned.**

Keywords-serious educational games; player-centered; proposition logic; truth tables; multiple intelligence; TrueBiters.

I. INTRODUCTION

Since years, the logic course in the 1st year of the bachelor program of Computer Science at our university has been a stumbling stone. On average less than 30% succeed in the exam on the first try. Dealing with a formal language and a high level of abstraction is difficult for most of our students. Although the course starts by explaining and illustrating the relevance and usefulness of logic in Computer Science, the students easily lose interest and exhibit procrastination. After a while, lots of students are completely lost. We tried to remedy this in different ways, i.e., by enriching the teaching material with illustrations, giving more concrete examples, the paradox of the week, and mandatory homework. However, these efforts were not successful. Since educational games deemed to be an enjoyable way to foster learning and given our own research on serious games, we decided to develop an educational game for the course and investigate whether this could remedy some of the issues.

The game is inspired by the two-player competitive card game “bOOleO” on boolean logic [1]. We replaced boolean logic by proposition logic and digitized the game. The digitalization has the advantage of allowing for the automatic verification of the correct use of the rules of proposition logic when applied by the player. We developed the game for smartphones as most students have a smartphone and smartphone games are popular among them. The development was done in an iterative way. Each version was evaluated, improved and reevaluated.

The paper is organized as follow: in section II we review other educational games related to teaching logic. In section III we describe the principles of the gameplay. Section IV presents the different iterations in the development and section V discusses the different evaluations. The results are discussed in section VI. Section VII concludes the article.

II. RELATED WORK

One of the first educational games related to logic and introduced in 1982 was Robky’s Boots [2]. In this game, children are introduced to the basic operations of logic (AND, OR, and NOT), which they can use to construct “machines”. The game was perceived as “intrinsically enjoyable and interesting by its players” [2].

A prototype of a narrative-based interactive learning environment for teaching binary arithmetic and logic gates (AND, OR, NOT and XOR) is described in [3]. The environment uses a fantasy narrative, i.e., a computer on a ship that acts as the tutor and tests the player’s understanding through a series of tasks. The results of the evaluation on learning using pre and post-tests and a control group showed that the game improved the test scores of the players. Furthermore, the players perceived the game as enjoyable.

In [4], a game-based multi-touch table environment for learning as well as practicing propositional logic is presented. The authors also address the problem of low retention and high dropout rates of computer science students in the early phase of the study due to topics such as mathematical logic. The focus of this game is on the method of resolution in propositional logic. The logical concepts are taught in a very abstract way, similar as in textbooks, and the practicing also takes place on the same level of abstraction.

The results of the evaluations indicate that the game was perceived as easy to use, helpful, fun and motivating. However, the evaluation was mainly on usability and player experience and not on learning outcomes.

In [5], the development of web-based tools for teaching logic is described. Prolog+CG tools concerning syllogisms and propositional arguments have been developed as web applications using gamified quizzing. For instance, for syllogisms, the learner is given an argument and the learner must evaluate the validity of the argument. When the user has got a certain fixed number of correct answers in a row, he or she wins. In a similar way, software tools, such as LogicPalet [6], exist that help students to master the basic concepts of logic. Although, this kind of tools may be valuable, they are not real games.

What distinguishes our game from these works is that our game purely focuses on practicing the truth tables. We also include the IMPLY and EQUIVALENT operators and tried to reduce the abstract level of the subject matter.

With respect to non-digital games, “bOOleO”, the game on which our game is based, is a strategy card game based on the principles of boolean algebra. It is a two-player competitive game, and the goal is to reduce a list of bits by building a pyramid using logical gates. Similarly, in [7], a board game, “The Logic Game” was proposed for learning the truth conditions for the logical operators. An experiment with students taking a logic course showed that playing this game had a significant impact on their skills and understanding of logic. Similar to our game, this game is presented as complementary material to the regular teaching. The principles of the game are very similar to ours, but it is using the regular symbols for the truth-values and operators, and in this way does not deal with the issue of logic’s formal and abstract notation. Other non-digital games to teach propositional logic are WFF ’N PROOF [8] and the propositional logic card games proposed in [9], but these games focus on learning inferences or proofs in logic.

III. Principles of the Gameplay

TrueBiters is a digital single- or two-player game for practicing the basic logical operators of propositional logic: AND, OR, IMPLY, EQUIVALENT, and NOT.

The game starts by generating six random binary values (bits), representing truth-values: 1 represents TRUE and 0 represents FALSE. They are placed at the top of a reverse pyramid containing tiles (see Figure 1) that the player must fill up in such a way that the bottom tile corresponds to the rightmost value of the initial list of bits. Filling in the pyramid is done step by step, by applying each time an available binary operator on two bits; in this way two bits are reduced into one bit. For instance, the OR-operator applied on 0 and 1 will result in the value 1. The opponent has the same goal but for a pyramid starting with the six bits inverted. Each player has several logical operators at his disposal that he can use to fill the pyramid. At every turn, the player can reduce two bits into one. The first player that achieves the goal is the winner. In the single-player mode the player wins by simply completing the pyramid correctly.

The binary operators are represented by fictive creatures (i.e., monsters) that eat two bits and spits out one bit. Representing the logical operators by monsters is done to reduce the level of abstraction and make the reduction process more concrete. Each type of monster has two versions: one that spits out the 1-value and one that spits out the 0-value (see lower part of Figure 1 for some monsters). This reflects the fact that the application of a logical operator can result in TRUE or FALSE depending on the input values and according to the truth table. As such, when reducing two bits into one, the player should not only know which type of monster to use, but also which version of the monster. If a wrong monster version is used the reduction is invalid and the turn is over. This will stimulate the players to become very familiar with the truth tables of the logical operators, which was our goal.

There is also a creature that represent the NOT operator. A player can use a NOT-creature to counter the progress of the opponent. A NOT-creature swaps the value of one of the initial bits. If used well, this action will invalidate several of the reductions made by the opponent. However, as the application of this monster also effects the player’s own initial list of bits, he has to use this with care because it can also invalidate a number of his own reductions; it is only beneficial to use the NOT when the damage is bigger for the opponent. This requires the player to reason about the possible consequences on all operations already applied in the game.

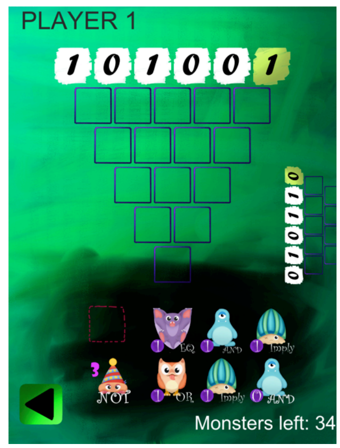

Figure 1. Screenshot of the start screen for the 2-player version

The game has different levels of difficulty: easy, medium, and hard. At each difficulty level, the types of monsters, as well as their number vary, and for the difficulty levels medium and hard also a timer is used.

IV. Development

The initial version of the game was developed in 2016. This version was using an Android tablet to render the board and each player was using an Android smartphone that contained the player’s stack of cards (i.e., the monsters). Only one card was visible at any time. Figure 2 shows this set up. The player could inspect the cards by

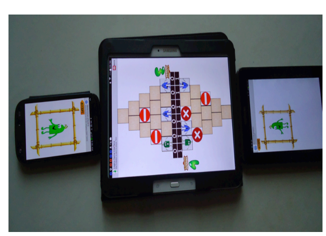

Figure 2. Set up of the initial (first) version of the game

swiping left and right and could place a card on the board by swiping the card up. The three devices were communicating through Bluetooth.

Based on a first evaluation, a timer was added to limit the time taken by a player to make a reduction, requiring the players to be more familiar with the truth tables. We also adapted this version to be usable in a larger-scale experiment. A logging mechanism was added to keep track of winning/losing and of the mistakes made.

The first two versions of the game required two or three devices: one tablet (for the board) and one (in case of one player) or two smartphones (for two players). Although using a tablet to hold the board seemed like a good idea, it prevented us to roll out the game, as a lot of devices were needed. Therefore, it was decided to drop the tablet. This required a new design in which the game board and the cards deck had to be integrated on a relatively small screen. Moreover, the original version was only available for Android OS. In order to make the game available for multiple platforms, it was decided to re-develop the game using technology that would make it easier to support Android as well as iOS.

In autumn 2017, this resulted in a new version with both single- and two-player mode, available as app and as Web-application. The single-player mode was using one device, while the two-player mode could be played with one or two devices. In the new setup, by default the player sees his own pyramid (Figure 1) but can also inspect the pyramid of the opponent by swiping. When only one device is used, the players share the screen. In this case, the players can see each other's monsters but not at the same time.

Also, this version was evaluated on usability and game experience. Based on the feedback received, the game was further improved: the distribution of operators for the different levels were revised; the 'look and feel' was improved; difficulty levels where added with the possibility to enable or disable collecting points. Moreover, a leaderboard was added, as this was an explicit request of different participants in the evaluations. TrueBiters is now available for free, respectively from the Apple Store and Google Play.

V. Evaluations

Each version of the game was evaluated for its game experience using GEQ [10]. We will not discuss these evaluations in detail, as their main purpose was to improve the game from the usability and game experience points of view. Instead, we will focus on the evaluations related to the learning effect and the suitability for the target audience.

In addition to its main purpose, i.e., improving the knowledge of the truth tables of proposition logic, we also developed the game as a case study for our research on player-centered serious game design. In that research [11], we were investigating whether taking individual differences among players into consideration during game design could be beneficial for the game as well as for the learning experience. In particular, we explored the use of the theory of Multiple Intelligence (MI) [12] developed by Gardner in 1983. The theory of MI states that all human beings have eight relatively independent intellectual capabilities (called *intelligence dimensions*) and that individual differences between people are the result of the strength of these intellectual capabilities and how they work together. Although this theory explicitly deals with individual differences in terms of learning capabilities, research that relates it to serious game design and that studies its merits as a determinant for adaptation, is rather scarce. We recognize that there are controversies about this theory. Opponents (e.g., [13], [14]) criticize the lack of strong empirical evidence for the existence of the dimensions, while proponents (e.g., [15]) argue that the value of such a theory is rather in the contributions it could make to the practice in the field. We follow the proponents and see the theory as a possible useful mechanism for personalization and therefore we investigated whether this theory could be used in understanding players' behavior and motivation for using a game, and to adapt games accordingly. Therefore in a number of our evaluations we also measured the level of the different "intelligences" (as defined by MI) of the participants by means of the MI questionnaire MIPQ [16].

A. Pilot Evaluation

Before rolling out the game in our logic course, we first performed a pilot study to investigate the potential learning outcome of the game, as well as the game experience. This was done with the first version of the game. Details of this pilot study can be found in [17]. In short, our results revealed that when considering the dominant MI intelligences of the players, those who had the logical-mathematical intelligence as one of their dominant intelligences learned the most from the game. In [17], it is investigated why this game suits this dimension of MI by analyzing the used game mechanics.

B. Second Evaluation

The next evaluation was done with the second version of the game. It took place in the academic year 2016-2017. For this evaluation, the students following the logic course were divided into a control group and an experimental group. The control group (27 participants) received the classical exercises on truth tables under the supervision of a teaching assistant, while the experimental group (23 participants) played the game after a short briefing session. The groups were uniformly composed based on the results of the mathematics test that our students do at the start of the academic year.

Both groups first performed, under the guidance of the teaching assistant, some classical exercises on truth tables. At the start of the experiment, they completed a pre-test and at the end a similar post-test to verify the learning effect.

Based on the data from the pre- and post-test, our first hypothesis: "*participants who played the game will make less mistakes in using the logical operators than those who did not*" could not be accepted. We actually saw that in their post-test, the students in the experimental group made significantly more mistakes (p =.004, mean for control group = 1.30, mean for experimental group = 3.65), as well as with the IMPLY operator (p=.000, mean for control group = 0.22, mean for experimental group = 2.57).

This last result could be explained as follows. At each step of the game, the participants had several operators to choose from, and based on our observations during the experiment, almost all participants tended to ignore the IMPLY operator. Presumably, this is because students perceive this operator as the most difficult operator to understand, remember and apply. Therefore, the students in the experimental group did not adequately train with this operator, while in the exercises (made by the control group) there is an emphasis on the use of this operator. As the difference between the numbers of mistakes is only significant with respect to this operator, this is most probably the cause for observing a significant difference in the total number of mistakes made. One way to remedy this situation is to enforce the equal use of all operators in the game or even force to practice the IMPLY operator more. For this purpose, we adjusted the distribution of the operators in the different levels of the game in the next version of the game.

C. *Third Evaluation*

As we already performed an experiment related to comparing learning outcome, we decide to set up another type of experiment in the following academic year (2017-2018). In that year, the students of the logic course were introduced to the game during a class session. They received a briefing of 15 minutes, and then played the game for 20 minutes. Afterwards, students were asked to practice with the game voluntarily in their free time. A manual and a tutorial clip were available. On the mid-semester trial (written) exam of the course, students were asked if they had continued playing the game or not. If so, we asked for how long; if not, we asked why not (using an open question). Students who had played the game were also given questions about their game experience. The trial exam was only on proposition logic and included exercises that explicitly tested the knowledge of the truth tables. The final exam covered all the subjects of the course, i.e., also predicate logic and lambda calculus. We analyzed the results using a t-test, considering the students that continued to play the game as the experimental group and the others as the control group. Slightly less than half of the students (30 out of 63) had played the game after the introduction. They played the game between 15 to 150 minutes, mostly in the self-training mode. These students obtained clearly higher marks on the final exam, i.e., there was a significant difference between the experiment (Mean=13.70, SD=3.4) and control (Mean=10.81, SD=4.75) groups ($t(59)=2.724$, $p < .01$). However the difference was only significant for the final exam, not for the trial exam.

There was in general no correlation between the time spent on playing and the results of the trial exam, except that those who played most (4 students played between 120 to 150 min) failed the trial exam. We discuss this in section VI.

Reasons given for not having played the game were: not enough time (7x); felt no need to practice (6x); no suitable device (5x); preference for the classical exercises (3x); forgot to do (3x); missed the introduction session about the game (3x); preference to use the time to study (1x); feeling that it was not helpful and boring (1x).

D. *Fourth Evaluation*

The game was also used in a workshop for pupils of the 3rd grade of secondary education (16 to 18 years old) (November 2017). The main goal was to investigate whether the game would also be usable in secondary education for teachers willing to take up logic as one of the elective subjects. (Note that logic is not a mandatory subject in our secondary educational system.) The participants, 21 pupils, first received an introduction to proposition logic (35 minutes), then they practiced individually for 10 minutes, and next they played against each other. The workshop lasted 90 minutes. At the end of the workshop, the pupils were asked to fill out an online questionnaire about their background (age, educational program, game experience, etc.), issues experienced with the game, their perceived learning experience, and their general opinion about the game. Most pupils were following a STEM-oriented education. Although they reported some usability issues, they were positive and could see the potential of the game.

VI. DISCUSSION

A. *Adapted to the Target Audience*

The nature of the courses in the Bachelor of Computer Science requires a good level of logical reasoning and mathematical abilities. Therefore we decided to tailor the game design towards the logical-mathematical intelligence dimension of MI. Based on the recommendation given by [18], we applied mostly game mechanics that are suitable for this dimension, i.e., *logical thinking*, *strategizing*, *modifier*, *quick feedback*, and *points*. Although, the work recommends to not use the mechanics *timed*, *disincentives*, *choosing,* and *placing* for this MI dimension, we did so for the following reasons. *Timed* was added because different participants mentioned that a timer would make the game more challenging. However, to accommodate players that do not like a timer, it is only used in two of the three difficulty levels. *Choosing* and *placing* are core mechanics of the game, and therefore it would be difficult to avoid them without changing the principles of the gameplay. We used *disincentive* (losing a turn in case of applying a bad operator or losing points) as a feedback mechanism for enhancing learning. The pilot evaluation showed that indeed logically-mathematically intelligent players had better game experience (see [17]).

B. *Learning Outcome*

There was no significant difference in learning outcome on the subject of the truth tables between the control group and the experimental group in the second evaluation. This allows us to conclude that playing the game has the same learning effect as the classical exercise session under the supervision of the teaching assistant. This justifies the use of the game, because it means that a part of the traditional exercise session can be replaced by playing the game, in this way freeing up time for other more complex topics and allowing the students to practice the truth tables autonomously, more intensively, and at their own pace. In addition, we also have seen a major increase in the passing rates for the course after the introduction of the game. Of course, after two years, it is still too early to substantially attribute this to the game.

C. Use as Didactical Tool

The experiment done in the last academic year has taught us that only introducing the game and leaving the students free to use it, is not enough to incentivize everyone. The reasons given for not playing the game were mostly related to a lack of motivation, while a learning game is supposed to motivate to study. Apparently, this was not the case for a portion of our students. Possible explanations are:

1) Some students simply do not like to play games and may therefore be reluctant to play. We hope to remedy this by providing them more time in the class to try out the game.

2) Some of the students were not convinced that playing the game would have an added value. This could be remedied by giving positive testimonials of other players.

3) Maybe the game was too boring or not appealing enough to some students. The game experience evaluation showed that most participants were positive about the game, but that it could be more challenging. Therefore, we will organize competitions between the students (e.g., in teams) and reward them in some way.

4) Perhaps, for some students the aversion for logic is far greater than their intrinsic motivation to play a game. Gently pushing the students to play the game in combination with competitions and rewards could be a solution for this.

Furthermore, we noticed that the students who played most (4 students played more than 120 min) actually failed the mid-semester trial exam. So, we see the potential danger that some students keep playing too long and do not spend enough time on studying the content of the course. However, not offering the game anymore will not remedy this. Students with an intrinsic motivation to play that is far greater than their intrinsic motivation to study will always spend a considerable amount of time on playing.

VII. Conclusions

This paper presents the development and evaluations of TrueBiters, an educational game to practice the truth tables of logic. The game was tailored for logically-mathematically intelligent students. The main principles of the game were taken from an existing board game. The game was developed in an iterative way. During this process, the game was evaluated in different ways. Based on the results of the evaluations we can conclude that from a game experience and learning perspective, the game is well suited for its target audience and has the same learning effect as the classical exercise session under the supervision of the teaching assistant, which means that it can be used as a replacement for this session. However, we also noticed a lack of motivation with some students to play the game voluntarily Therefore, a better embedding into the course is needed.

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