Scientific Discovery Games for Authentic Science Education

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Abstract: This paper presents results from the design and testing of The Quantum Computer Game, a game that allows players to help solve actual scientific challenges in the effort to develop a quantum computer, which is a computer where individual bits can be both 0 and 1 simultaneously – potentially offering more computational power than all conventional computers combined. The main objective of scientific discovery games is to facilitate collaboration between researchers and gamers, but the focus of The Quantum Computer Game, in contrast, is multifaceted. The motivation for developing this type of game concept for science education stems from a critique that the way standardised skills are taught in today's school system leads to students becoming experts at consuming rather than producing knowledge. The primary aim of developing a game-based platform for student research collaboration is to investigate if and how this type of game concept can strengthen authentic experimental practice and the creation of new knowledge in science education as well as what elements play a central role in this. Researchers and game developers from the Department of Physics and Astronomy at Aarhus University and ResearchLab: ICT and Design for Learning at Aalborg University tested the game in three separate high school classes (Class 1, 2, and 3) and used video observations to record the students, aged 17-20, playing the game. Qualitative interviews were conducted with the classes and their teachers after the game sessions and all students filled out surveys with qualitative and quantitative questions. The focus of the various tests was to understand the motivational aspects of students playing this type of game and how students felt about participating in authentic experiments as well as to detect whether the game could offer new types of educational approaches to highly complex subject areas such as quantum physics. The tests in the first two high schools showed that collaboration with researchers and contributing to research in quantum computing were highly motivating factors. In a survey with multiple possible answers conducted after the game session students were asked to state what the most interesting aspect of playing the game was. To this question 69% answered "To participate in real scientific research", 69% answered "To solve physics problems" and 31% "To play games". This is an interesting result as games in education often are viewed as a tool to motivate students to participate in educational activities. Here games become a tool to frame or facilitate processes where the motivation lies in the subject the game covers or in the research context outside the school context. Designing a game that facilitated professional research collaboration while simultaneously serving to introduce high school students to quantum physics at their level proved, however, to be a challenge. When asked whether they had learned about physics from playing the game using a five-point scale ranging from 1 for "not at all" to 5 for "a lot", 8% of the students in Class 2 answered 1; 46% answered 2; 23% answered 3; 23% wrote 4 and no one checked 5. The third round of testing in Class 3 incorporated a didactic design developed to integrate the game into a laboratory classroom setting that involved simulations, theoretical work and physical experiments to strengthen student expertise in these areas. When asked whether they had learned about physics, 14% answered 1 ("not at all") and 7% answered 2, while 36%, 14% and 29% answered 3, 4 and 5 ("a lot"), respectively. The results presented in this paper show that scientific discovery games and the fact that they make participating in authentic scientific experiments possible is highly motivating for students. The findings also show, however, that the learning design in the class setting must be considered in order to improve the students' experience of learning and that various design challenges remain to be developed even further.

Keywords: Scientific discovery games, science education, quantum computing

1. Introduction

Teaching with the use of games and simulations in school science education was introduced in the 1970s and in the early 1980s the potential of games and simulations as a new teaching tool was discussed extensively (Ellington et al., 1981). In the early 1990s the first IT-based games for the exploration of the natural sciences and technical subjects were developed (Egenfeldt-Nielsen, 2005). After the turn of the millennium, there has been an increasing awareness about the possibilities new types of commercial computer games can offer science teaching, but also about developing new formats framing aspects of real-life science learning environments that allow players to tackle complex problems in simulated professional contexts (e.g. Squire & Klopfer, 2007; Magnussen, 2007). These games have proven to support new practices in science education, such as in student development of new professional inquiry tools adapted for schools, innovation in networks of new types of non-school actors, e.g. fictional characters and authentic professional tools, and processes for the imaginative creation and representation of new knowledge (Magnussen, 2008).

More recently, scientific discovery games have been developed where player contributions to real-life research practice are an integral part of the game. The prime example of this type of games is the game Foldit where complex scientific problems are translated into puzzles and a game-like mechanism is provided for non-expert players to help solve the problems presented (Cooper et al., 2010). The current paper presents the preliminary design considerations and initial test results of a scientific discovery game for an in-school learning environment. We also discuss the potential and challenges of developing scientific discovery games for science education to enable students to work with unsolved scientific problems and the creation of new scientific knowledge.

2. Background: Gamified research collaboration in science education

One of the main focus points in the development of science game formats over the past 10 year has been how the medium of games can introduce new approaches to authentic science education (Gee, 2003). Prime examples of this are profession simulation games that simulate some of the objectives and environments of a specific profession by using the technology, tools and/or methods of that profession. The motivation for developing these types of games stems from a critique of the teaching of standardised skills to children in today's school system. It is argued that few schools teach students how to create knowledge; instead, students are taught that knowledge is static and complete, which means they become experts at consuming rather than producing knowledge (Sawyer, 2006). As a result, the medium of games has been used to create environments with simulations of complex real-life situations, where students have to think like professionals and solve problems in innovative ways, just as professionals do (Shaffer & Gee, 2005).

Interesting issues arise, however, in relation to this class of games that need to be addressed when discussing the integration of creation of new knowledge and authentic science practice in science education. Even though the games integrate professional values and tools, they remain *simulations* of professional practices. This aspect of the games brings up the matter of whether students learn to work *as* a scientific expert or whether they learn how to *be* a scientific expert. This may depend on various design elements of profession simulation games. First, the clients and experts students collaborate with in the games are fictional characters with fictional problems that need to be solved to play the game in school but that do not have relevance in the world outside school. Second, the fictional problems to be solved in these games often follow a linear path and have a clear starting and end point. This is clearly different from real-life professional problem solving, where the processes are more multidimensional. Finally, even though these types of games have been shown to support student creation of new process tools, the solutions are often pre-defined and already known by the teachers. This stands in contrast to the real-life open-ended tasks professionals face and that can be carried out in various ways, the chance of success or failure always an issue to be considered.

Scientific discovery games address these issues that exist outside a formal learning setting. The main goal of this type of game is to create a platform that motivates players to contribute to solving scientific problems. One example, Foldit, mentioned earlier, is an online puzzle game where players participate in folding amino acid chains into new protein structures. Presented with a primary protein sequence or partially folded structure, players must find the lowest-energy three-dimensional structure, which can also be an unknown protein structure (Cooper et al., 2011). Players manipulate the protein structure by pulling, twisting and tugging the protein backbone and side chains into various configurations (Good & Su, 2011).

Scientific discovery games contain specific design features that distinguish them from the majority of other games (Cooper et al., 2010; Good & Su, 20011). First, scientific discovery games are designed for non-expert players to advance a scientific domain. As a result, the visual features and graphics must make it possible for beginners to experiment with highly complex solutions and scientific information. This requires that the game interface must be designed to introduce beginners to a highly complex field while simultaneously motivating them to play the game. Another distinctive feature of this class of games is that the puzzles do not have any pre-defined solutions; even the game designers do not know the answers, of which there are potentially more than one. This also implies that the interactive design must make exploration and experimentation processes possible while simultaneously respecting real scientific constraints. Consequently, the scoring mechanism must reward multiple player strategies while remaining true to the latest knowledge about the scientific phenomenon (Cooper et al., 2010; Good & Su, 20011).

Various design features have to be reconsidered when designing scientific discovery games for an educational context. First of all we need to consider what new elements this class of games brings into science education. Scientific discovery games have the potential to introduce real-life experiments and the processes behind the creation of new scientific knowledge into school science, but determining which aspects of an online game and the classroom are central for students to experience and engage in the open-ended scientific inquiry process is necessary. Moreover, we also need to understand what the main motivating factor for playing this type of games in school is; is it, for instance, competing against other students, contributing to science or collaborating with scientists? Finally, other issues that need to be addressed are the implications of introducing this type of games for different types of students and the role of the teacher. How do students experience their learning in this type of games and will this class of games be reserved for the brightest students or will the less theoretical, more experimental approach employed open up complex subjects to other groups of students? The focus of this paper is to present the design and initial test results of the adaption of a scientific discovery game The Quantum Computer Game to a school environment in order to teach quantum physics to high school students in Denmark, and to discuss the potential and challenges of designing this type of game for school science education.

3. The quantum computer game

The Quantum Computer Game represents a collaborative effort between researchers in physics, computer science and game-based learning at the interdisciplinary Aarhus University Ideas Pilot Center for Community-Driven Research, established January 2012. The focus of the quantum game project is the research-based production of a game-based platform for player participation in quantum computing development and research.

3.2 The game

Quantum computers are based on the principles of quantum mechanics and It has been proven that quantum computers will be able to perform certain important tasks much faster than all of the conventional computational power combined (Shor, 1994; Grover, 1996). The basic problem that players have to solve in the game is the optimisation of the transportation of atoms in a quantum computer (see figures 1 and 2) (Weitenberg, et al., 2011). We anticipate a community contribution on several levels. The computers were initially programmed to try out multitudes of transportation paths but failed to find the optimal ones. As a result the hope is that the graphical representation of the problem in the game will enable the human players to find better paths. This approach will be effective not only due to the sheer quantity of potential players but also because players can potentially apply the distinctly human skills of pattern recognition and intuition to perform a much more intelligent optimisation than computers can. Furthermore, an important aspect of in the Quantum Computer Game is extensive user participation in the initial design phase and in subsequent extensions.

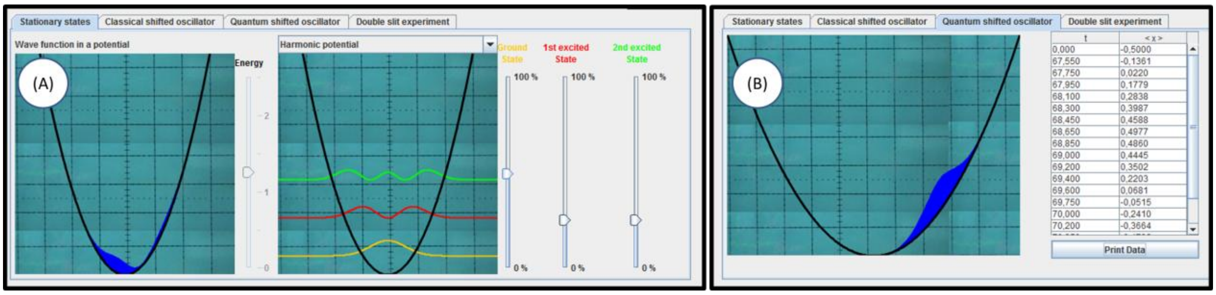

Figure 1: Examples of tutorial games to introduce the quantum mechanical concepts and methods needed to understand the scientific challenge. (A) An illustration of the allowed quantum mechanical states and sliders to create mixtures of these. The basic lesson is that if the atom (represented as liquid like substance inside graph) is purely in one of the allowed states of the well, it will not move in time but in a mixture it will. (B) An atom is agitating in the well. The user then has to remove the kinetic energy by moving the well from side to side. The data on the position of the atom versus time is listed to the right, allowing students to transfer the information to a plotting program to analyse the results of their experiment.

The game has two parts. The first part consists of tutorials that introduce players to quantum physics and that teach them how to operate the game (figure 1).

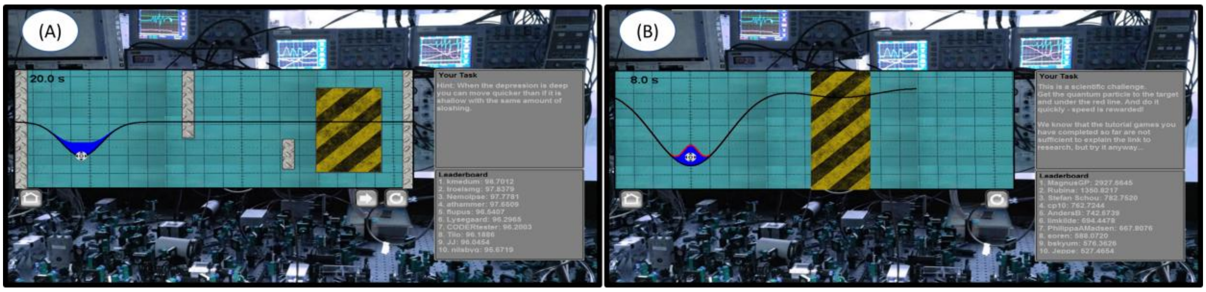

Figure 2: In this scientific part of the Quantum Computer Game players must move an atom (represented as liquid like substance inside graph) from the starting position to the target area (striped) by dragging the well. The scientific objective is to complete the transport without any agitation in the final position. (A) An introductory challenge where players must transport the atom without hitting the walls. (B) The real scientific challenge where players must keep the atom under the lighter curve lining the atom.

Players can continue playing games in the tutorial or they can move on to the advanced part (figures 2 and 3) to begin solving real research problems and to have their performance logged.
The key scientific objective of The Quantum Computer Game is to develop algorithms with a small enough error probability to allow for quantum computations on a large scale without errors piling up. For each attempt that a player makes, a score is calculated based on the quality of the resulting quantum computer. The performance of every player is logged centrally and the overall highest score will always correspond to the state of the art of the research field and can thus be adjusted for each hour people play. The game also allows players to develop their own sub-games, thus permitting them to contribute computational results and take part in continuously developing the game.

4. Test of the Quantum Computer Game

The methodology used in developing the components of the Quantum Computer Game followed a design-based research process and involved various design cycles, interventions, analyses and redesign (Brown, 1992). The beta version of the game was completed in early 2012 and interventions were conducted in a number of high school classes and with online players. Results from two of the high school classes (Class 1 and 2) will be presented briefly below (Magnussen et. al, 2012). Based on results from the initial tests, the game was further developed and a new version was tested in April 2013 in a high school in west Denmark (high school 3). The test was not completed at the deadline of this paper, but preliminary results will be presented below.

4.1 Tests in Class 1 and 2

The beta version of the game was initially tested in two high school classes (Class 1 and 2) in February and October 2012, respectively (Magnussen et al., 2012). The results show both similarities and differences between the two settings. Class 1 consisted of 20 students 17-19 years of age in their second year of high school, while Class 2 comprised 20 students 17- 20 years of age in their last year of high school. Due to the nature of Danish high schools, or *gymnasier*, which follow a three-year curriculum, this meant that the students were in consecutive grades. Quantum physics had been introduced by the teachers in both classes. Quantum physicists from the development team introduced The Quantum Computer Game to the classes and conducted the testing over two class periods. Game play was recorded on video for later observation and semi-structured interviews were conducted during the test with individual students and afterwards with the whole class. The classes were also asked to fill out a written survey after the test answering qualitative questions such as "What was the best worst/part of playing the Quantum game?" and "How does playing the Quantum Game differ from your other physics teaching?" and quantitative questions such as "Rate the following - Have you learned physics by playing the game?" where students were asked to rate the statement on a scale from 1 (not at all) – 5 (a lot) Both classes tested an early beta version of the game (figure 3).

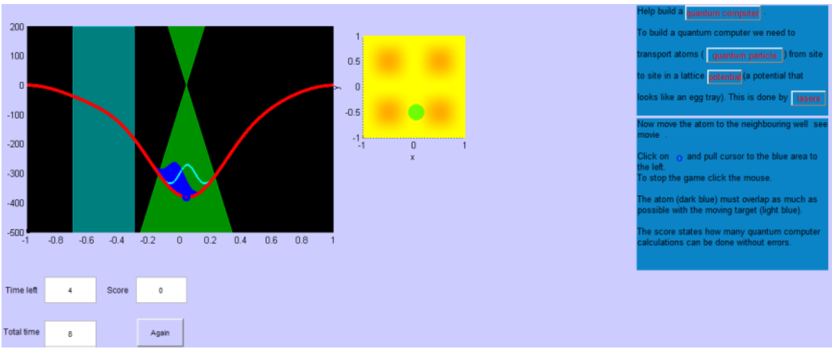

Figure 3: An early beta version of The Quantum Computer Game tested in high school 1 and 2. Players had to move the atom from a well on the right to a well on the left while agitating the atom as little as possible.

As the individuals involved in the project represented developers, physicists and researchers in digital learning design, the initial testing included several points of focus, one of which was to understand what motivates players using this type of game. A central aspect of this class of games is the collaboration with researchers and the reason why determining whether or not this is a primary motivating factor is important. We wanted to ascertain whether the gaming elements that scientific discovery games share with other games, such as competing for high scores, also serve as a motivating factor for gamers in scientific discovery games.
We conducted a number of similar observations in the two high school classes where the game was tested. Initially intensely interested and very motivated overall, the students in the two classes worked continuously with the game during the two class periods where we did observations. At the end of the second class period, some of the students had begun to lose interest. This was especially the case for the youngest group of students from school 1. The test was set up so the students had to download the game on their own laptops prior to the test session. The majority of the students used their own laptops, but a few shared laptops in groups of two or three. Students in Class 2 were asked to try the sub-games on the Quantum Computer Game platform. In both classes, students discussed strategies and patterns for how to transport atoms in different environments as they played. They also discussed their scores and commented on results, high scores eliciting cheering and various remarks. Scores thus apparently seemed to be a central motivating factor for the students, but results from the qualitative interviews with the classes after the test and written survey show that other elements also played a role in motivating players. The answers provided during the interview and on the survey students filled out after playing the game varied in relationship to what participants thought was the best part about playing the game.

The survey was completed by 7 out of 20 students. To the question "What is the most interesting part about playing the game?" 57% of students in Class 1 answered "To participate in real scientific research", 14% answered "to solve physics problems, 14 % answered "To play games" and 14% answered "To participate in real scientific research, to solve physics problems, to play games". In the qualitative interview with the whole class the class was asked what the greatest difference between playing the game and their normal teaching was and one student stated that, “In the normal teaching you only calculate the results, while in the game you get the feeling of directly doing the experiment”. When students and (after the interviews with the students) teachers were asked to expand on this comment, they explained that what happened in the game felt like an experiment compared to lab work done in class, which they saw as demonstrations and the theoretical premise for understanding the experiment.

Class 2’s answers to questions to motivational factors differed slightly but overall showed the same results. In a survey with multiple possible answers conducted after the game session students in Class 2 were asked to state what the most interesting aspect of playing the game was. To this question 69% answered “To participate in real scientific research”, 69% answered “To solve physics problems” and 31% “To play games”. These results are interesting as games in education often are viewed as a tool to motivate students to participate in educational activities. Here games become a tool to frame or facilitate processes where the motivation lies in the subject the game covers or in the research context outside the school context. One student described what he felt was the most interesting aspect of playing the game as knowing, “that you have a real chance to help enable a quantum computer. It also irritated me when I didn’t get as many points in the game as my friends did, which got me to play the games even more.” In response to the same question about what was most interesting, two other students explained, “The best thing about the game must be that it is one of the few games in this world that you can actually use for something” and “that they were relevant to physics, and that you have the chance to make a difference, even if it’s not a vital one, in the development of quantum computers (Cool!)”. The first answer indicates that the focus some students have on scores does not necessarily exclude a focus on research collaboration, whereas the two subsequent answers show that it is primarily, if not exclusively, the fact that they are contributing to research that motivates them to play the game. During the interview conducted immediately after the test in Class 2, 2 - 3 students also said that they did not feel as if they had learned about physics. They explained that this was because moving the atoms was a simple task that did not expand their understanding of quantum physics. The survey results also showed that a larger part of the students had the esperience that the game did not teach them physics to a significant degree. When asked whether they had learned about physics from playing the game using a five-point scale ranging from 1 for “not at all” to 5 for “a lot”, 8% of the students in Class 2 answered 1; 46% answered 2; 23% answered 3; 23% wrote 4 and no one checked 5.In the interview with the teacher after the test session, the teacher challenged the understanding that students had of “learning about physics”. He argued that their understanding of it was to practice to be able to complete assignments and added that the contact with the researchers and the game had given his students a deep understanding of quantum mechanics that he could not have given them. The teacher interpreted this as stemming from the strong focus the class had on the subject and from the fact that the students had to be prepared for their final exams.

In summary, the results from these two classes showed that the main motivating factor proved to be research collaboration or solving physics problems and that 54% of students in Class 2 had the experience of learning none or little physics form playing the game. The game and setup in the class thus provided a strong experience of participating in an authentic experiment, but a less evident experience of learning physics form the participation. Teachers in both classes also commented on the different “tangible” approach the games had to a highly theoretical subject. In Denmark, high school physics is taught at a highly theoretical level, which may be the basis for the student comment that students “only calculate the results” in “normal” teaching, but that the game gave them the feeling of “directly doing the experiment”.

4.2 Test in Class 3: Experimenting with strengthening the student experience of learning

Class 3 comprises a second-year high school class consisting of 20 students 17-20 years of age from a technical high school in west Denmark. The test in high school 3 has not yet been completed, which means that our initial observations are only preliminary, but worth including briefly to support the discussion of possible solutions to the design challenges involved in scientific discovery games.

The feedback and findings from the tests conducted in high school 1 and 2 pointed the redesign of The Quantum Computer Game to a different focus. Part of the new focus for the further development of the game was to strengthen the student experience of participating in an authentic science experiment as this had proven to be a strong motivating factor for some students. Moreover, our hypothesis was that the authentic research collaboration aspect of the game could contribute with new didactical input to science education. One of the ways we strengthened the authentic aspects of the game was to make the researchers more visible on the game's website scienceathome.org by including their pictures and by adjusting the graphics to match the atmosphere of the physics lab where data from the game were actually being used to develop a quantum computer.

Another issue that the project group responded to with regard the second test was making improvements on what the teachers had commented on as having a tangible approach to a highly theoretically subject. We interviewed the teacher at high school 3 on this topic and other subjects before the test and she had observed that this "more intuitive" approach to a highly theoretical subject appealed to a group of students that was exceedingly interested in the subject, but felt that it was difficult. These teacher's observations were in keeping with teacher comments from high school 1, where teachers commented that the game allowed for a more tangible approach to a theoretical subject. As a result, the test focused on investigating this issue further, but the final results have not yet been compiled.

The final area of focus for implementing and testing the game in high school 3 was to strengthen student learning on the subject at both an experimental and theoretical level. Groups of students in Class 1 and Class 2 had explained that they did not feel that they had learned any physics while they were playing the game. Before testing the game the class teacher, in collaboration with the coder team, developed a didactical design focused on implementing theoretical approaches, experimental practice using physical tools and play with game simulations. The goal was to boost the authentic aspects as well as the theoretical and experimental practices by assigning students roles in the game as experts. This design was inspired by elements of simulation games on specific professions (Magnussen, 2007) described earlier in this paper and notions of collaborative learning (Dillenbourg, 1999). The game test session in Class 3 was conducted over four school periods and had been introduced in previous lessons by the teacher. The first session included an introduction to a simulation of a professional setup where the students introduced to a professional setup were they were a research team of physicists working on the development of a quantum computer by optimising the movement of your laser to transport atoms. Students were divided into three different teams, each one representing an area of expertise. One group comprised experimental physicists who was working on understanding the movement better by doing analogue experiments. The second group of experts was IT professionals specialised in simulations who did virtual experiments in the games. The last team worked theoretically and focused on understanding the mathematics behind the various elements of the movement. The teacher assigned students with skills suited to the expertise of the different teams. Students worked in groups with similar expertise for three class periods and were then mixed with students with different expertise with the goal of sharing results and to produce a poster or film with their conclusions. Overall students worked intensively with the game in the different teams. The simulation of the different professional approaches in the authentic framework of contributing to the scientific domain of these professions appeared to spur complex discussions concerning the results obtained from using physical experimental tools compared to the virtual experiments in the game.

In the survey after the game students were asked whether they had learned about physics, 14% answered 1 ("not at all") and 7% answered 2, while 36%, 14% and 29% answered 3, 4 and 5 ("a lot"), respectively. In summary results in this class showed that 79% of students answered 3 or above I Class 3 compared to Class 2 where only 46% answered 3 or above. In Class 2 no students answered 5 (have learned a lot physics) which differed to Class 3 where 29% answered 5. The data are preliminary and have not yet been fully analysed the above results indicate that the new design has strengthened the students' experience of learning physics.

5. Discussion and Conclusions

The results presented in this paper show that scientific discovery games and the fact that they make participating in authentic scientific experiments possible is highly motivating for students. The findings also show, however, that the learning design in the class setting must be considered in order to improve the students' experience of learning and that various design challenges remain to be developed even further. In order to successfully develop and introduce scientific discovery games into science education we need to focus on how the game operates and the didactical aspects that can strengthen importance elements in these games, such as authenticity and authentic experimentation. This paper described how a scientific discovery game can be didactically designed to fit a classroom setting by merging aspects from simulation science games about specific professions with the research collaboration approach.

Other elements of importance we have detected are that the complexity of playing the game needs to correspond with the complexity of the scientific challenge. Another aspect that needs to be investigated further in future research is how this type of games can be applied for motivating weaker students in science education. In interviews with teachers from Class 1 and 3 the teachers stated that the intuitive or tangible approach of the game to quantum physics encouraged the weaker students to participate more actively. The student responses describe in this paper indicate that scientific discovery games must apply new approaches to integrating authentic knowledge creation and scientific practice into school science education for specific groups of students. Moreover, it needs to be further investigated how role playing and collaborative learning approaches can further strengthen the student learning experience and the outcome of that learning.

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