PhyGame: An Interactive and Gamified Learning Support System for Secondary Physics Education

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***Abstract*—With the rapid development of affordable digital technology, digital transformation is progressing in different sectors of society. Education is no exception; especially online education has been widely spreading since the coronavirus pandemic. While online education enables individuals to overcome the constraints associated with traditional offline formats (e.g. flexibility regarding time and place), it also poses several challenges. Particularly, in STEM subjects that require hands-on experience, there are limits to what online education can offer. Therefore, online education platforms for such subjects should be developed with a goal to replicate offline hands-on experience as much as possible. It has been reported that many learners lose their motivation and drop out of online courses. Previous research has shown that virtual hands-on experiments are vital for enhancing learners' motivation. Taking these factors into consideration, we have developed a system called PhyGame for secondary-level students' physics education using interactive elements and gamification. Through evaluation by 44 secondary-level students, the system has been proven to be an effective learning platform for learning physics with enjoyment while maintaining a high level of student motivation and engagement.**

***Keywords*—Gamification; interactive learning; online education; engagement; STEM**

I. Introduction

In recent years, the remarkable development and increased use of digital technology has forced many educational institutions to change the way they provide educational services and adapt to the times. Typical examples of such changes include reliance on cloud services such as online educational tools and online video conferencing tools. However, significant challenges remain to be solved in adapting STEM (science, technology, engineering, and mathematics) education from a face-to-face format to an online format. Previous research has pointed out that the teaching-learning process of scientific concepts, especially pertaining to physics and biology, involving young pupils poses significant challenges for both learners and educators [1], [2], [3]. Therefore, there is an urgent need to develop lesson materials and learning support systems for effective teaching and learning. In conventional education, textbooks have been the main source of teaching materials. While conventional textbooks can provide a lot of information in text and visual illustrations, they often portray only static situations, i.e., scientific concepts cannot be visualized in motion. Therefore, PhyGame, the learning support system presented in this paper provides a simulation environment where students can instantly observe a scientific concept in motion by modifying the parameters and performing related calculations. This boosts interactivity and consequently learning, as interactive learning has been reported to be at least six times more effective than passive learning [4].

Another problem with online and digital education is related to the difficulty of retaining motivation by students. Let us consider the example of MOOCs, demand of which skyrocketed during the COVID-19 pandemic [5]. MOOCs platforms provide access to educational contents in a flexible manner that is not constrained by time, location, or number of students. However, past studies have shown a trend of low engagement and motivation in MOOCs, with only 7-13% of users completing the programs [6]. The main reason for this is that it is difficult for learners to maintain their own motivation [7]. In order to solve this motivation problem, we utilized digital gamification in PhyGame. Previous studies have confirmed that gamification contributes to improved learning outcomes, motivation, and engagement [8], [9], [10].

The contribution of this paper is fourfold.

- We have developed PhyGame, a system for learning physics for secondary-level students that can be operated with a standard web browser and is available at https://phygame.org/. The system incorporates several game elements, including points, badges, and leaderboards, as well as a simulation environment for interactive learning. For reasons of flexibility in design and implementation, we developed the system from scratch rather than customizing any existing learning management system.
- PhyGame supports three different modes corresponding to three different difficulty levels so that students can adjust the learning curve according to their needs.
- In addition to gamification and interactive simulation, PhyGame provides analytics support for both learners and educators. Learners can immediately confirm their performance and have a visual understanding of their weaknesses and response patterns. Educators can also obtain visual information about students' performance.
- We conducted a three-pronged evaluation of PhyGame: (1) User study by high school students and teachers, (2) evaluation by Octalysis gamification framework, and (3) evaluation of performance of webservice by open-source tool. Promising results were obtained in all three aspects.

The rest of this paper is organized as follows. In Section II, we present related research. Section III and Section IV describe the design and implementation of PhyGame respectively. Sections V through VII presents the detailed evaluation results, and Section VIII discusses the issues and the current status of resolving them. Finally, Section IX concludes the paper.

II. Related Work

Gamification, which is one of the central concepts in this paper, has been widely used in the context of education [11]. Gamification is defined as "the use of game mechanics, aesthetics, and game thinking to engage people, motivate behavior, facilitate learning, and solve problems" [12]. The concept of gamification has been applied in many fields and incorporated into many educational tools.

A. Gamification-based Systems in STEM

In the following, we present several gamification-based systems in the field of STEM. ChemCaper™: Act I - Petticles in Peril [13] is a chemistry learning game. The system features a unique storyline that combines elements of character adventure and chemistry. Players can learn chemical concepts while manipulating molecules and elements. Foldit [14] is an online game that analyzes protein folding for students aged 10 and above. The system challenges players to predict the optimal folding structure of a protein. One of the most important features of this system is its ability to contribute to actual scientific research. Quiz and Treasures [8] is a learning platform where students can learn English words and vocabulary, mathematics and computer science through quizzes. Players can earn experience points and badges by answering questions correctly, and each point earned will increase their levels. Bonde et al. developed Labster for secondary-level education, which allows common laboratory experiments to be performed on digital terminals [15]. The system incorporates game elements such as storytelling and animation to facilitate learning. Furthermore, the study confirmed that combining simulations with traditional education significantly improved learning outcomes and increased motivation.

B. Gamification-based Systems Related to Physics

Next, we present several gamification-based systems related to physics. PhET Interactive Simulations [16] is an interactive simulation platform that can be used for science education in schools. The system covers a wide range of scientific fields, including physics, chemistry, and biology, and can simulate specific experiments and phenomena. Students can intuitively use the system while learning scientific principles and concepts through hands-on experience. Fantastic Contraption [17] is a physics-based puzzle game for students aged 10 and above. In this system, the goal is for players to build machines by combining different parts and solving puzzles using the laws of physics. Students can enjoy learning physics while using their creativity and problem-solving skills. Universe Sandbox [18] is a space simulation software for students aged 10 and above. The system is characterized by its ability to simulate the behavior of celestial bodies such as planets, stars, and galaxies based on the laws of astrophysics. Users can enjoy learning about the formation of the universe, celestial collisions, and the effects of gravity. Crayon Physics Deluxe [19] is a physics puzzle game for all ages. The objective of the system is to simulate the behavior of objects painted by the player according to the laws of physics and to solve puzzles. The process of solving problems helps develop free thinking ideas and physics-based thinking. Algodoo is an educational application designed for children and teachers [20]. It aims at supporting the acquisition of fundamental physics principles through an engaging and interactive learning experience. The application takes a visual approach with an intuitive interface to present the subject matter. It uses interactivity and a physics engine to create objects, allowing learners to gain practical skills in understanding and applying real-world physical laws. World of Goo is an engaging puzzle game designed for children [21]. Players are required to construct structures based on physical laws of the real world. The game allows players to naturally learn and deepen their understanding of physics concepts by completing different stages with limited resources. Furthermore, the game provides a sense of achievement for each stage completed, thereby encouraging a positive learning experience. Monster Physics® [22] is an interactive application designed to promote the attainment of basic physics concepts through an engaging and enjoyable learning experience. The user learns fundamental physics concepts through the construction of objects and the completion of missions. A feedback feature is incorporated into the design, enabling learners to assess their progress and identify areas for improvement in preparation for the next challenge. The app engages learners in critical thinking and creativity through repetitive challenges, thereby fostering their interest in the field of physics.

III. Design Considerations of PhyGame

One of the main goals of PhyGame was to create a digital environment in which physics concepts can be simulated interactively. Simulation is a dynamic means of observing different states of a phenomenon and can promote user engagement, both in terms of being able to visualize the behavior while changing parameters, and in terms of being able to immediately check the results of one's calculations. Visualization is important in science learning, and the immediate feedback ensures that students can continue learning without a teacher next to them. With these design goals, the developed system PhyGame has the following characteristics:

1) Incorporation of gamification elements such as points, badges, leaderboards, simulations, etc.
2) The development of three modes (Simulation Mode, Multiple Choice Questions (MCQ) Mode, and Text Quiz Mode) that can be set according to the learner's level of understanding.
3) The creation of an interactive simulation environment.
4) Accumulation of learning logs and provision for feedback on learning analysis.

A. Mode Design for Easy Adaptation to Learning Stages

Three modes were designed to allow all learners to choose a better learning environment. The three modes are, in order of anticipated use, simulation mode, MCQ mode, and text quiz mode.

1) Simulation mode: The simulation mode is intended for users with a limited understanding of physical phenomena and allows them to visually understand the phenomena while using the simulation. It is intended to be used by students who have difficulty or are reluctant to learn by referring to textbooks or other conventional sources.

Fig. 1 shows a typical screen in simulation mode. The problem statement and conditions are given in the top half of

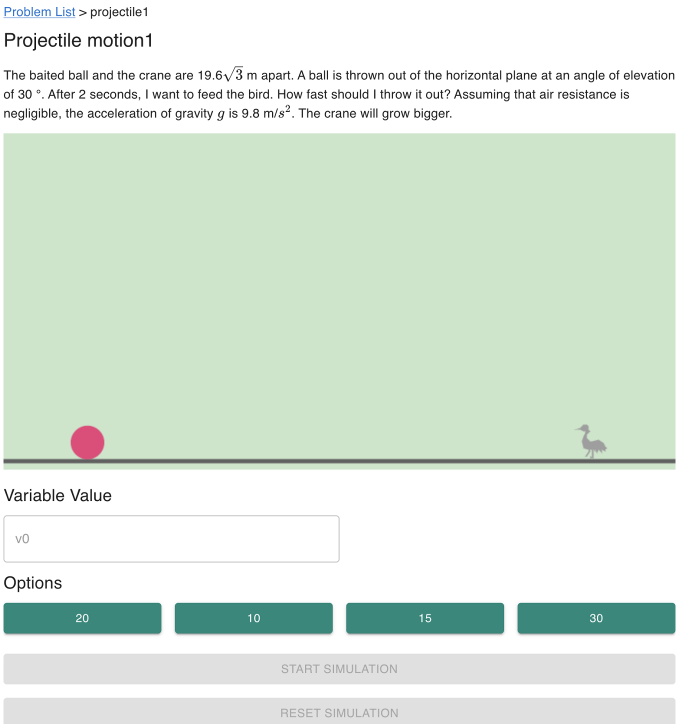

Fig. 1. An example of simulation mode page; projectile motion.

the page. In this example the user calculates on paper to derive the initial velocity v_0 in projectile motion. Then choose the correct option from the four alternatives. When the simulation start button is pressed, a red object (bait) is launched at a speed calculated by the user. Compared to static materials such as textbooks, the user's ability to view a simulation of projectile motion, utilizing parameters set by the user himself, leads to careful observation of whether or not the target is hit. If the user makes a mistake (in other words, does not hit the target), he or she can press the reset button to enter the answer again. Since hitting the target has a game-like charm, it is believed that such approaches will have a positive impact in maintaining students' motivation.

2) MCQ mode: MCQ mode is used when the user understands the contents of the study and can visualize the phenomena, and it excludes the simulation screen from the simulation mode. Students can check their ability to operationalize mathematical formulas by calculating the formulas at hand and choosing the answer from a list of alternatives. Furthermore, the fact that the simulation is not displayed requires the learner to be able to organize the situation from the problem statement and to imagine the phenomenon in concrete terms.

3) Text quiz mode: The text quiz mode is intended for users who already have a good understanding of what they have learned. It is intended to be used to check the level of understanding before the regular examinations. The mode does not include any game elements, and it was designed for students who are already motivated to test their physics skills.

B. Game Elements Used in PhyGame

PhyGame includes several game elements, which, together with their objectives, are as follows:

1) Simulation: An element that combines a story with game-like content, allowing users to immerse themselves into a simulated world and interact in it.

2) Badge: Certifies the achievement of a certain level of learning. For example, Fig. 2(b) can be earned by answering 100 questions correctly regardless of the mode.

3) Point: PhyGame uses this to indicate experience. Experience is earned by challenging problems, answering questions correctly, and earning badges. When a certain number of points are earned, the player's level increases.

4) Leaderboards: Allows students to check their own progress relative to their learning status.

5) Progress indicator: Shows the experience value. Even if the experience value can be seen numerically, it is just a number. On the other hand, if users can understand how much effort it takes to raise their level, they will be motivated to study more.

6) Difficulty setting: This refers to the various modes. By changing the range of responses according to the individual's level of understanding, all learners can learn at the appropriate difficulty level.

C. Target Users and Learning Content

We designed the system with secondary-level students as the main target users. The learning contents were designed in accordance with the curriculum guidelines for secondary-level physics established by the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) [23].

A total of eight simulations were designed, and priority was given to the scope of study, which was assumed to be easy for learners to understand by incorporating dynamic simulations. Simulation environments are provided for the following topics. projectile motion, law of conservation of momentum, moment of force, Newton's universal gravitation, constant velocity circular motion, refraction of light, prism, and convex lens.

D. Analytical Function

The analysis function was designed to allow learners to easily monitor their own learning progress and understanding. Learners can view statistical data on questions and their own learning results by question, mode, and genre. Moreover, educators also have access to the data of learners in the classes they manage. This allows the classroom administrator to immediately assess the level of understanding in the classrooms, thereby taking appropriate preparations for remedial lessons.

E. Badge Design

One of the most common game elements is a badge that users can earn for solving problems. Fig. 2(a) shows the PhyGame badge. In PhyGame, users can earn badges by fulfilling certain conditions. Many gamification systems use badges that use universal shapes such as stars or regular polygons.

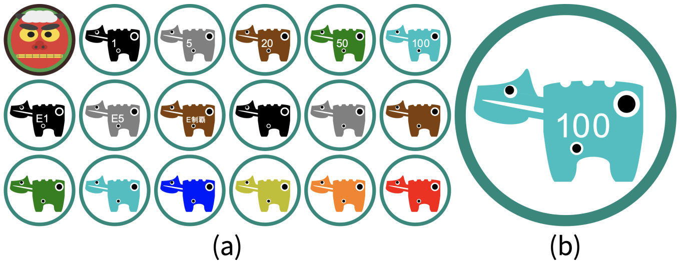

Fig. 2. (a) An example of badges in PhyGame and (b) enlarged version.

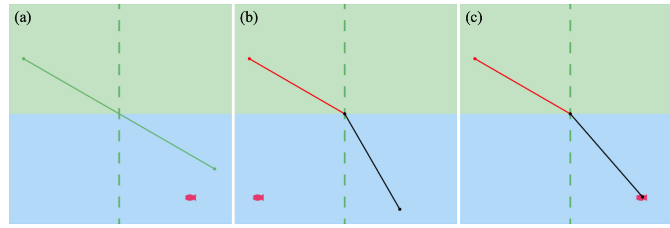

Fig. 4. An example of light refraction simulation in PhyGame: (a) initial state; (b) incorrect answer, fish escaping from a harpoon; (c) correct answer, the player catch fish.

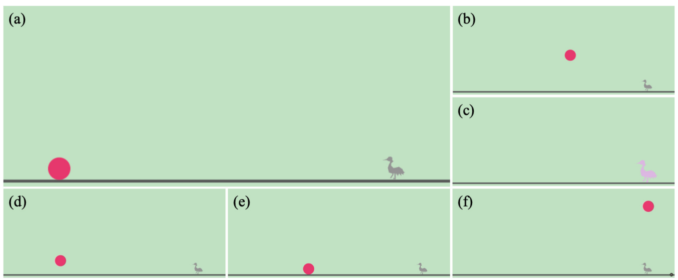

Fig. 3. An example of projectile motion simulation in PhyGame.

However, in selecting the badges, PhyGame respected the concept of culturally responsive teaching [24] and adopted motifs of traditional Japanese creatures with good omens, such as akabeko (legendary red cow) and shishigashira (lion's head). The color of the badge indicates the amount of experience gained. For example, in Fig. 2(b), if the player answers 100 questions correctly, regardless of the mode, he or she will receive a light blue sticker representing 500 points. By collecting badges that users can earn under different conditions, we hope to motivate them to continue learning.

IV. Implementation of PhyGame

This section describes PhyGame from a technical aspect. The system is available in Japanese and English for use at https://phygame.org/.

A. Examples of Simulations within PhyGame

In the following, we present two of the eight simulations. Some of the other simulations can be found in our previous publications [25], [26]. Simulations were developed to be more intuitive. It was also developed on the premise that it would be used for practice problems after the relevant formulas were covered in class, in order to provide a visual understanding of how the formulas are used in concrete terms. A short video clip introducing some of the simulations can be found in [27].

1) Projectile motion: A projectile moves horizontally with a constant velocity linear motion with velocity $v_0 \cos\theta$, and vertically with a vertical throw-up (assuming upward is positive) motion with initial velocity $v_0 \sin\theta$ and acceleration $-g$. Eq. (1-2) and (3-5) relate to horizontal and vertical motion, respectively.

$$
\begin{aligned}
v_x &= v_0 * \cos\theta && (1)\\
x &= (v_0 * \cos\theta)t && (2)\\
v_y &= v_0 * \sin\theta + (-g)t && (3)\\
y &= (v_0 * \sin\theta)t + \frac{1}{2}(-g)t^2 && (4)\\
v_y^2 - (v_0 \sin\theta)^2 &= 2(-g)y && (5)
\end{aligned}
$$

The user can read the information on x, g, θ, and t among the variables that appear in the Eq. (1-5) from the problem statement and conditions, and solve the problem based on this information. For example, in the Fig. 1 problem, v0 is derived from x, θ, t using the equation (2). The results can then be entered as input values to answer simulations or questions.

In order to make the simulation more enjoyable for the user, the crane grows in size and color when it is hit by a red bait. Note, however, that although it is made to look like a game, it is only a part of gamification.

The following sections describe the screen transitions for projectile motion simulations. The initial state of the simulation in projectile motion is shown in Fig. 3(a). When appropriate values can be calculated, the cranes become larger and more colorful as the food impacts the cranes, as shown in the transition trajectories in the order of Fig. 3(a, b, c). On the other hand, trajectories that transition in the order of Fig. 3(a, d, e) or Fig. 3(a, f) are incorrect. In the case of incorrect trajectories, we see the food falling before the crane due to its slow initial velocity or passing over the crane due to its high initial velocity, respectively.

2) Refraction of light: If the angle of incidence is θ_1, the angle of refraction is θ_2, the (relative) refractive index of medium 2 relative to medium 1 is n_{12}, the (absolute) refractive index of medium 1 is n_1, and the (absolute) refractive index of medium 2 is n_2, the relationship $n_{12} = \frac{\sin\theta_1}{\sin\theta_2}(= \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2} = \frac{n_2}{n_1} = \frac{1}{n_{21}})$ is valid.

The user can read n_1, n_2, and θ_1 value from the problem statement and conditions, and combine these with the trigonometric functions table to solve the problem. For example, derive θ_2 from the values of n_1, n_2, and θ_1. The results can then be entered as input values to answer simulations or questions. By using the simulation, the user can feel that he/she is making meaningful calculations.

In the following sections, the screen transitions of the light refraction simulation will be explained. The initial state of the

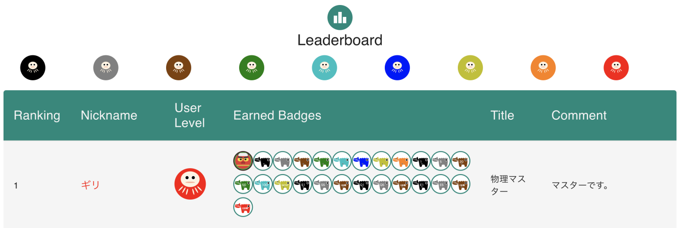

Fig. 5. PhyGame's leaderboard.

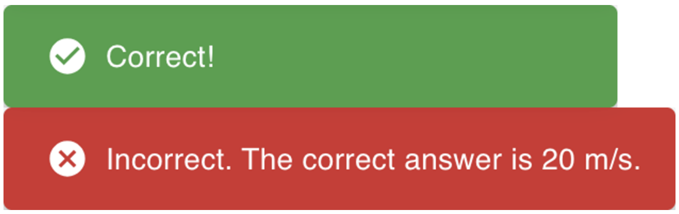

Fig. 6. An example of feedback in PhyGame.

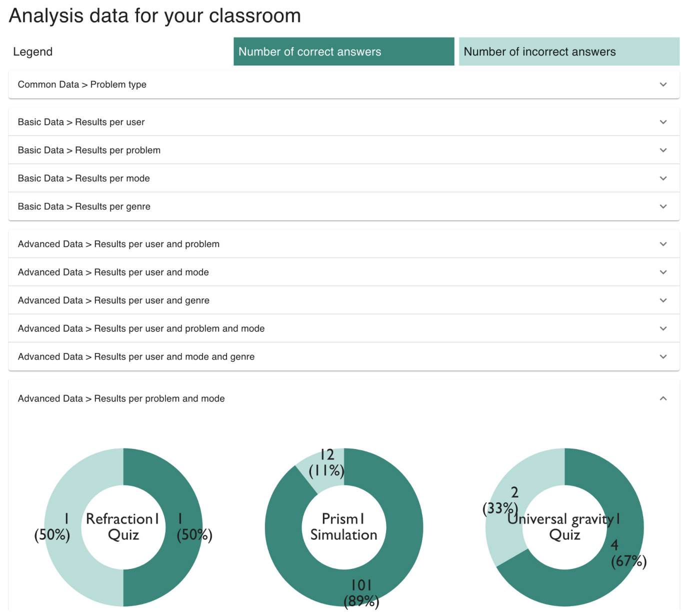

Fig. 7. An instructor's analytics interface in PhyGame.

simulation of light refraction is shown in Fig. 4(a). Deepen your knowledge of light refraction through a simulation of using a spear to catch fish in the water. The green line represents the whole spear, the red line symbolizes the spear visible above water, the back line represents the spear in the refracted area underwater, and the red fish is the target of this problem. The user must calculate the refractive index and set the correct angle of incidence so that a spear entering the water will hit a fish that appears to be in a different location due to refraction. If the user sets an incorrect angle of incidence, the fish swims away to the left of the screen, as shown in Fig. 4(b). On the other hand, if the user can set the correct angle of incidence, the spear will hit the fish and catch it as shown in Fig. 4(c).

B. User Interfaces of PhyGame

1) Leaderboard: Fig. 5 shows the PhyGame leaderboard, which displays, from left to right, the rank, nickname, icon corresponding to the user's level, list of badges earned, titles, and comments. The users are listed in order of experience.

2) Instant Feedback to User Responses: When the user answers a question, the feedback shown in Fig. 6 appears in the lower left corner of the screen. The feedback confirms whether the answer was successfully saved in the database and shows a correct/incorrect decision. Fig. 6 is the feedback immediately after answering the projectile motion question. If the answer is correct, a green background is displayed with a statement indicating the correct or incorrect answer. If the answer is incorrect, "Incorrect" message and the correct answer are displayed on a red background. A policy of not showing the correct answer may also be adopted. In all cases, however, the system is set up so that an explanation is displayed at the same time as the correct or incorrect answer is determined. Thus, immediate feedback allows the learner to correctly understand the phenomenon and continue the learning activity regardless of whether the answer is correct or incorrect. PhyGame is an educational support system that assists learning in the classroom. While teachers will try to explain to students what they do not understand during the learning process, in reality, teachers are not always able to adequately respond to all students. This tool contributes to lowering the risk of losing motivation due to wrong answers and the associated risk of quitting the study midway.

3) Analytics for instructors: Fig. 7 is an example of the analysis screen that can be viewed by faculty members. The analysis data includes information on who answered which question and when, as well as the results. With this information, learners and educators can proceed efficiently with learning analysis. The three pie charts in Fig. 7 show some of the results classified by problem and mode. If we look at the rightmost graph, we can read that it represents the results of all the responses that solved the question "Universal gravity I" in "Quiz Mode," with 4 correct responses (67%) and 2 incorrect responses (33%). Because educators can track the responses of all students in the classrooms they manage, they can check the understanding of the entire classroom and begin providing assistance to individual students at an early stage.

V. Evaluation by High School Students and Teachers

A. Basic Data

In late 2022, we conducted a user evaluation at the Toyo University Keihoku High School in Tokyo. Participants were a total of 44 high school students and teachers in the science field. Assessments were conducted twice, one week apart, with 23 participants in the first week and 21 different participants in the second week. The students consisted of 13 first-year students, 13 second-year students, and 18 third-year students. Thirty students were male and eleven were female, and three students chose not to disclose their gender. Fig. 8 shows a photograph where students are evaluating PhyGame.

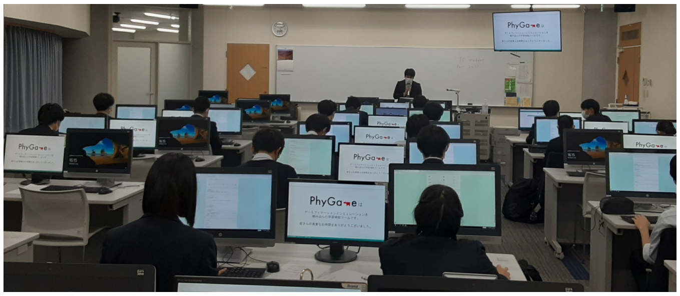

Fig. 8. High-school students testing PhyGame.

TABLE I. QUESTIONS IN USER STUDY FOR SECONDARY-LEVEL STUDENTS AND EVALUATION RESULTS

No.	Question	Mean	SD
Q1	Feeling of achievement	5.89	2.24
Q2	Feeling of immersion	6.45	2.50
Q3	Learning with fun	7.68	2.13
Q4	Improvement of motivation	6.52	2.78
Q5	Improvement of engagement	6.11	2.36
Q6	Willing to use for a different subject	8.14	2.54
Q7	User experience (UI/UX)	7.64	2.11
Q8	Overall rating	7.11	2.03
Q9	Comparison with traditional learning materials	6.73	2.20
Q10	Feeling of social connection	5.43	2.71
Q11	Favorite game elements	-	-
Q12	Good points	-	-
Q13	Points to be improved	-	-

B. Evaluation Item

The study employed a mixed research method, combining quantitative and qualitative evaluations. As shown in Table I, participants rated PhyGame on 13 items. A Likert scale from 1 to 10 was used for Q1 to Q10, with a rating of 10 indicating the highest rating. The reason for having an even number of Likert scales was to clearly identify whether PhyGame is viewed positively or negatively by not allowing the median value to be selected. On the other hand, some researchers argue that the median option should also be provided [28]. The reason for using the 10-scale method was to reflect the subjects' opinions as accurately as possible. In Q11, respondents were asked to select three of their favorite elements included in PhyGame in order of preference, while Q12 and Q13 were asked in the form of free-text questions. These questions allowed us to collect a wide range of information on the effectiveness, ease of use, attractiveness, potential improvements, and future development of PhyGame. Note that not all users experienced all eight simulations. As mentioned earlier, respondents included first through third-year high school students, of whom first-year high school students were only able to solve one type of problems (oblique projection) at the time of the evaluation. However, they tried all the simulations and enjoyed them. All second- and third-year students performed all the simulations.

C. Results of Quantitative Evaluation

Fig. 9 shows the result for each question from Q1 to Q10 by secondary-level students. According to Fig. 9 and Table I, PhyGame is an immersive and fun learning system that can increase motivation for learning. The materials were also evaluated favorably throughout compared to conventional materials, indicating a positive learning motivation to play in other ranges and subjects because of the favorable user experience. On the other hand, the factor of perceived social connectedness, which scored higher than the median but showed lower results than the other factors, needs to be added in future development.

The survey also asked about game elements that they liked throughout their PhyGame learning experience. The background of the research on this item is that many studies incorporating gamification into education have been conducted in the past, but it was reported that incorporating only points, badges, and leaderboards had limited contribution to motivation. This allowed us to test the acceptability of the simulation element, which is not a basic gamification element in this study, to secondary-level students. Fig. 10 is the top three favorite game elements. Fig. 10(a) shows that the most favorite element was also simulation, followed by leaderboards and difficulty adjustment in equal numbers. Fig. 10(b) also shows the favorite game elements by rank. According to the results, the simulation element is the most popular, followed by the difficulty settings and badge elements. Since some of the data had missing values, they were treated as invalid data.

D. Results of Qualitative Evaluation

In addition to the 10-point scale, we asked for a wide range of opinions on what was good and what needed improvement, as well as other free-form comments. Many cited badges, simulation, user experience, and analytical functions as positive aspects. On the other hand, many of the comments regarding feedback were received as points requiring improvement. Some of these opinions are presented below. User opinions are quoted without changing the wording as much as possible, with only typographical and grammatical corrections.

- "Since simulations are not possible with the paper textbooks I usually use, I can understand the phenomenon when I don't understand it, which makes it easier for me to study. (Also, when I make a mistake,) I think that understanding the phenomenon helps me remember it better, and I am less likely to make the same mistake when I try to solve the problem again."
- "The simulation makes it easy to understand what I am looking for now, and I can visually see what the object will do when I get the answer wrong."
- "The simulation allows you to visually grasp the movement of what you have learned and to understand it intuitively, whereas the graphical explanations in textbooks and problem books are not intuitively understandable."
- "The analysis of the areas I have studied is very easy to read, and I can efficiently learn my weak areas, etc."

The comments from the good points read that many users have improved their engagement toward learning by utilizing the system with the simulation built in. On the other hand, many of the comments that needed improvement were requests for feedback that would make it easier to learn, such as responses to wrong questions or a hint function for use in preparatory studies.

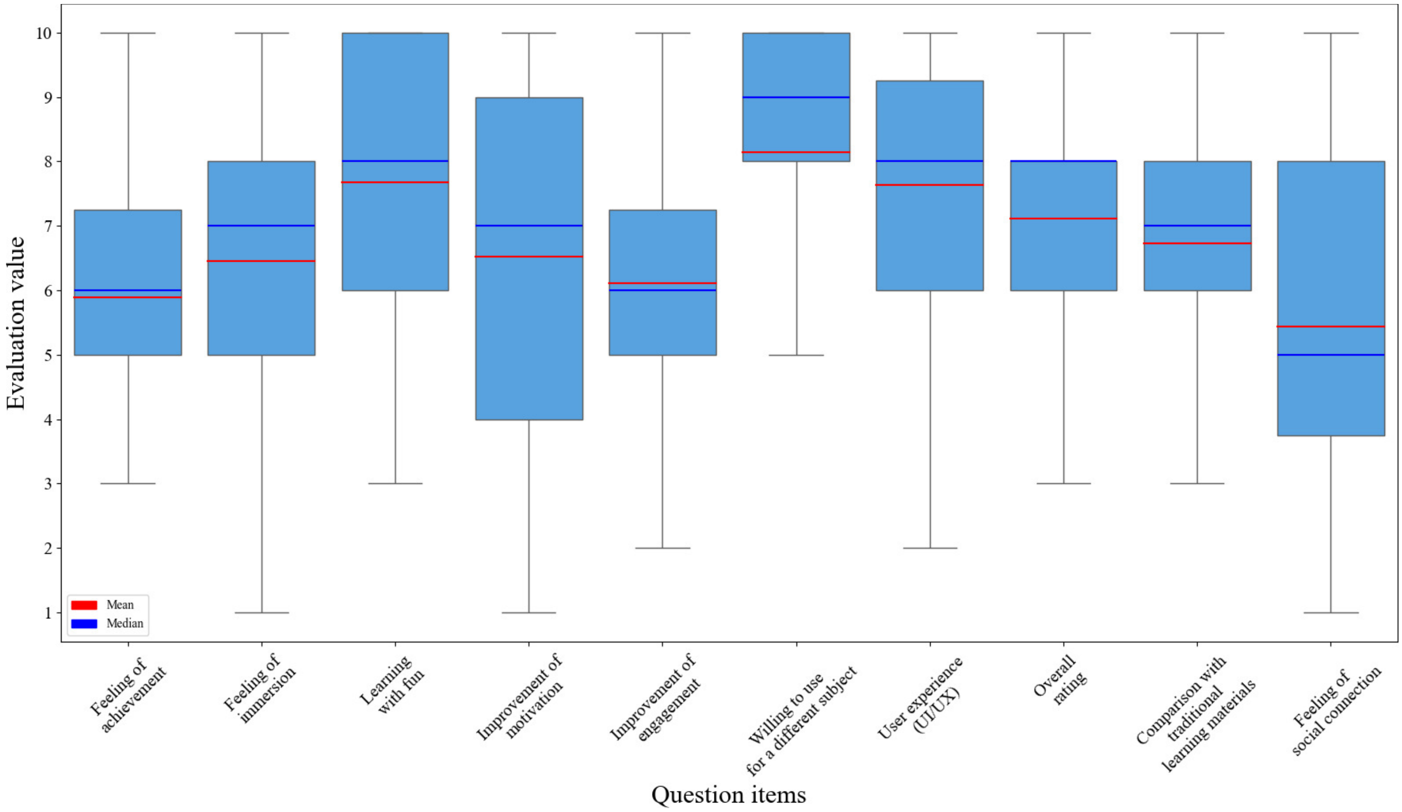

Fig. 9. Result of user study. Boxplot showing spread of scores with corresponding quartiles obtained for Q1 through Q10.

- "It would be easier to study if there was a button to display the answer instead of immediately displaying the answer when you make a mistake."

- "I would like to see a hint function because sometimes I don't understand even the easiest questions when I use it for preparation."

E. Evaluation from Teacher's Perspective

In this evaluation, we asked not only the students, but also one teacher who is actually teaching in the field for his opinion, the result shows in Table II. After the teachers observed the students using the system, the functions that only the teachers could operate (classroom-wide analysis and problem registration functions) were explained to the students in about five minutes. When a questionnaire was administered after the students had completed their evaluation, they rated the analytical function highly (highest rating on a scale of 10), and they also rated it highly (8 on a scale of 10) throughout. When asked about how to incorporate PhyGame into actual classes and the hurdles to introducing PhyGame, the respondents answered that there is still room for improvement in terms of operability, the number of simulation types and problems, and the UI. The results suggest that the system will be sufficiently practical and easy to use for everyone, with many learners and educators able to take advantage of it.

TABLE II. EVALUATION ITEMS AND ANSWERS FROM TEACHER'S PERSPECTIVE

No.	Question	Answer
Q1	Analytics function	10 (rating out of 10)
Q2	Willingness to use PhyGame in classes	5 (rating out of 10)
Q3	Improvement in teaching with PhyGame	5 (rating out of 10)
Q4	Overall evaluation	8 (rating out of 10)
Q5	How do you want to use PhyGame in classes?	We would like to incorporate simulations so that each student can solve (understand) the problem while showing the simulation.
Q6	What do you think will be the challenges in incorporating PhyGame in classes?	Ease of operation and visual clarity. The operations should be made as simple as possible so that students can quickly get used to the system.
Q7	What other features would you like?	Functions to watch videos of experiments and real phenomena.
Q8	What did you like about PhyGame?	It is a game-like system that makes it easy for students to engage with their studies.
Q9	What aspects of PhyGame should be improved?	The number of graphics and simulation patterns should be increased.
Q10	Other comments	Physics is difficult to teach on in the classroom, and in practice, it ends up being just note-taking in the classes from students' perspective, but this system will make it easier for students to solve the problems on their own.

VI. EVALUATION BY OCTALYSIS GAMIFICATION FRAMEWORK

Octalysis [29] is a gamification framework to investigate whether a system is designed to motivate users. It provides

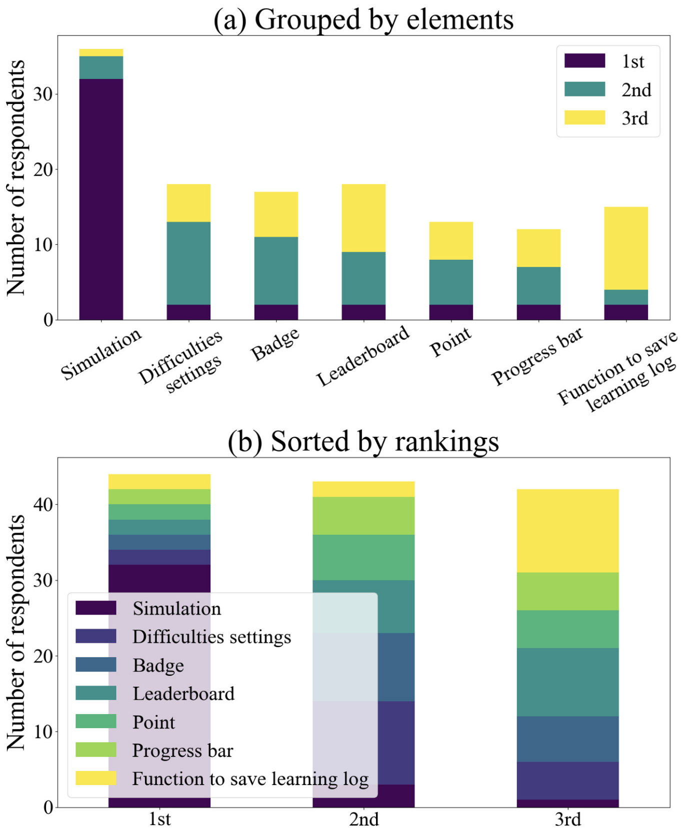

Fig. 10. Student's favorite game elements (a) grouped by elements; (b) sorted by rankings.

an intuitive interface called Octalysis tool which consists of eight evaluation axes, each with a set of factors that motivate the user, called core drives. For example, Core Drive 1 "Epic Meaning & Calling," indicates the degree to which users themselves are aware that they are doing something meaningful. PhyGame allows users to make their own simulation choices, giving them a sense of learning meaningful content. There are seven other core drives, and more detailed information is available from [30]. The white hat gamification, which indicates the upper side, is related to engagement, which makes positive feelings such as a sense of accomplishment stronger. Black Hat gamification, which shows the lower side, focuses on providing fear of losing psychological and financial rewards and on keeping the user motivated.

Overall, as reported by the Octalysis tool (Fig. 11), PhyGame exhibits a fairly balanced experience in terms of both left-brain/right-brain and white-hat/black-hat gamification. PhyGame tends to have strong white hat gamification properties and somewhat weaker black hat gamification properties. The nature of PhyGame's white hat gamification can be read as not requiring priority improvement, as it includes elements that give users a sense of accomplishment and positive user learning. PhyGame, on the other hand, is less critical and more predictable. Therefore, the nature of black hat gamification in PhyGame requires weakening the elements that reassure the user and adding more focused elements. To overcome this disadvantage, it is necessary to add new simulations, time limit functions, and other devices to increase the user's concentration.

In the left-right balance, Core Drive 3 "Empowerment of Creativity & Feedback" and Core Drive 7 "Unpredictability & Curiosity" are fully incorporated. On the other hand, the elements of Core Drive 6 "Scarcity & Impatience" and Core Drive 8 "Loss & Avoidance" must be strongly felt. To this end, incorporating badges that can be earned for a limited period of time and a system in which leaderboards are updated at regular intervals can motivate students to continue learning. The desire for Core Drive 5 "Social Influence & Relatedness" can also be satisfied by developing a function that allows anyone to freely create problems, and a multiplayer mode that allows multiple people to operate the simulation.

VII. Evaluation by Google Lighthouse

In order to evaluate the quality of the PhyGame webservice, we also evaluated it by Lighthouse [31] provided by Google Inc. Lighthouse is an open-source automation tool for improving the performance, quality, and accuracy of web systems [32]. It measures the performance of web pages based on the following criteria.

- First Contentful Paint (FCP): The time from the start of page loading until any part of the elements in the page is rendered on the screen.
- Speed Index (SI): Time how quickly the elements of the page appear in a human-recognizable form.
- Largest Contentful Paint (LCP): Time to load the largest element.
- Time to Interactive (TTI): The time it takes for a Web page to become interactive.
- Total Blocking Time (TBT): The total time that responses to user input, such as mouse clicks or screen or keyboard typing, are blocked.
- Cumulative Layout Shift (CLS): An indicator of how many unexpected layouts occurred during the display of the page.

Based on the above criteria with default weight factors, Lighthouse Scoring Calculator versions v8, v9 for Desktop devices estimated the performance of PhyGame site to be 100 out of 100. Therefore, it can be asserted that the webservice has no performance issues. The detailed result of the analysis with specific values for each criterion is depicted in Fig. 12.

VIII. Discussion and Future Work

With a view to harnessing the power of interactivity and gamification in secondary-level physics education, we developed PhyGame that supports in-browser simulation of basic physics concepts. Using PhyGame, students are able to learn interactively by observing principles of physics in motion by tweaking the parameters by themselves. We believe that such immersion beyond textbook knowledge deepens students' understanding. In addition, PhyGame also includes other functions like analytics tool for both students and teachers enabling them to keep track of study or class progress. As discussed in the previous three sections, we evaluated PhyGame on three fronts: User study by high-school students and teachers,

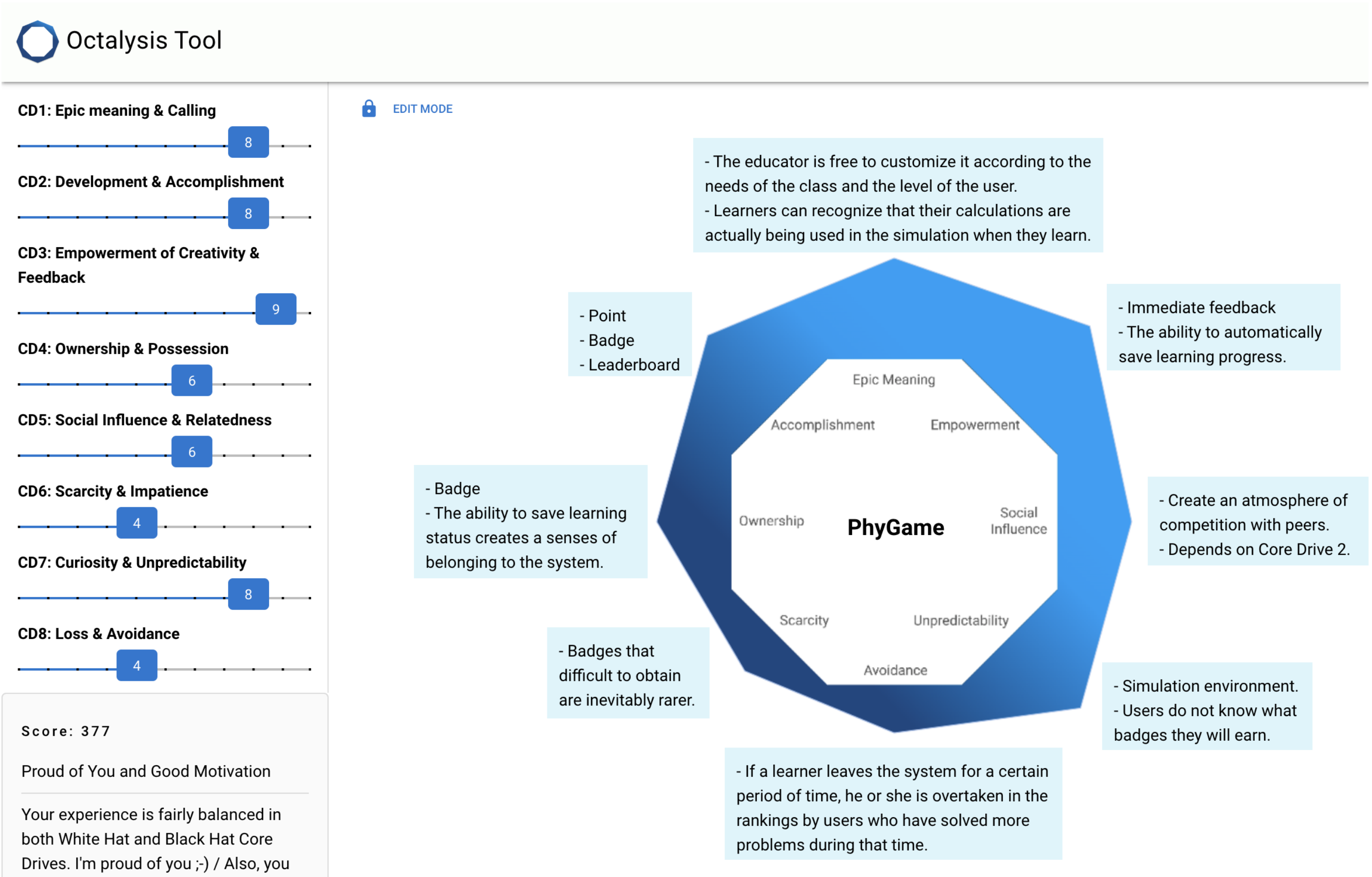

Fig. 11. An evaluation result of PhyGame using Octalysis tool.

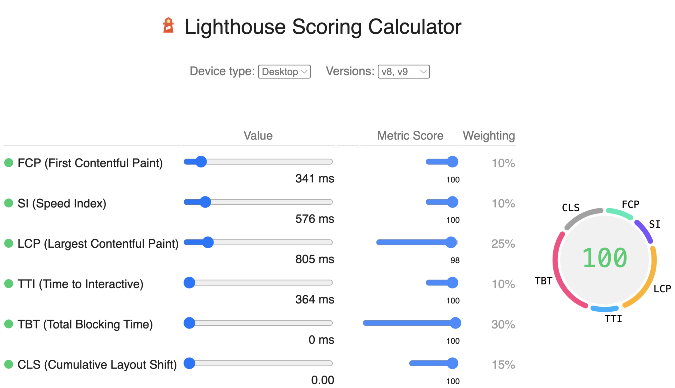

Fig. 12. Evaluation using Lighthouse; Desktop view version.

evaluation by Octalysis gamification framework to measure the impact on motivation, and evaluation by Google Lighthouse, a Chrome DevTool by Google Inc., for measuring the performance of webservices. All of these evaluations yielded promising results.

Many secondary-level students evaluated PhyGame as a learning support system having an easy-to-use UI and providing good user experience overall. Furthermore, they expressed the desire to learn other subjects using similar simulation and gamification-based systems like PhyGame. These results suggest that PhyGame successfully engages students and increases user involvement and motivation. The evaluation by instructor also highlighted the effectiveness of the analytics tool. However, there is room for improvement, which we consider as our future work. The two evaluation items that received relatively low scores (though greater than the median) in the questionnaire survey are the sense of accomplishment and social connectedness. We believe that the sense of accomplishment can be improved by increasing the number and types of simulations and diversifying the difficulty of the problems. Sense of social connections can be improved by introducing new problem-solving tasks in which multiple students work on the same task and collaborate with each other. In addition, although we considered culturally responsive principles for badge design, it is necessary to design badges from the perspective of universal design as well for users with color blindness and other physical challenges, by considering the shape and pattern of the badges. The text quiz mode required complete answers, including input of units, and no hints are also provided. Such restrictions may also need to be re-examined. From the viewpoint of evaluation, it is also important to observe how the system is used in actual classes and to objectively measure the learning effects of the system by dividing users into experimental and control groups and conducting tests before and after the use of the system.

According to the analysis of the Octalysis tool, PhyGame strikes a good balance between white hat and black hat core drives, and between left brain and right brain core drives, indicating a desirable balance between intrinsic and extrinsic motivation. However, as with many gamification-based systems, fostering intrinsic motivation remains a challenge [33]. A longitudinal study with PhyGame is needed to understand these dynamics.

Finally, according to the Lighthouse performance analysis, PhyGame webservice scores 100% on desktop computers. In future, we intend to optimize PhyGame web performance for mobile devices as well.

IX. Conclusion

This paper introduces PhyGame with the aim of facilitating the learning of physics for secondary-level students. PhyGame was designed to be interactive and fun to keep learning, to be able to operate in an online environment unaffected by the spread of infectious diseases, and to increase user engagement and motivation. To contribute to users' learning activities, we incorporated gamification elements such as simulations, points, and badges, and made it possible to display visual graphs from the learning logs for easy self-analysis. And in an evaluation by students from Toyo University Keihoku High School (N=44), many high school students expressed positive opinions about the learning experience. They also indicated that they would like to use a similar system when studying subjects other than physics. In this paper, we confirm that incorporating the concept of gamification into an online physics learning system increases secondary-level students' engagement and motivation in learning physics.

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