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Practical Use of an Error-based Problem Presentation System in Mechanics

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Abstract: Learners studying mechanics sometimes fail to learn correct scientific knowledge because of misconceptions they have from their experience with everyday phenomena. Error-based Simulation (EBS), which encourages trial-and-error by presenting a simulation based on the learner's solution, is effective in correcting errors. However, learners that make similar mistakes over a long period of time during the trial-and-error process tend to become stuck and fail to make progress in problem solving. In this study, we developed a system for adaptively providing auxiliary problems that address the areas in which stuck learners repeatedly make errors, helping them to overcome these errors and allowing them to progress. We evaluated the effectiveness of this system by testing it in a junior high school class. The results suggest that it was effective for junior high school students' learning.

Keywords: Elementary mechanics, Learning support system, Learning from mistakes, Error-based Simulation, Classroom practice

1. Introduction

Learners studying mechanics may not learn correct scientific knowledge because of misconceptions they have from their experience with everyday phenomena. Junior high school classes attempt to address this issue by providing learners with opportunities to obtain correct knowledge through experiments. However, experiments are costly and require teachers to provide learners with correct explanations of the phenomena involved.

Error-based Simulation (EBS) is an effective method for correcting errors (Hirashima et al., 1998; Hirashima et al., 2017; Horiguchi et al., 2005; Horiguchi et al., 2014). It is a learning support framework that visualizes learners' errors and encourages trial and error. EBS first presents a problem, and then based on the learner's answer to the problem, presents a simulation of what would happen if the learner's (incorrect) answer was correct. The incorrect answer causes the simulation to behave strangely, thereby making the learner aware that they have made an error.

One drawback of EBS, however, is that if a learner gets stuck on a problem in the middle of the trial-and-error process, then EBS can have difficulty helping the learner to overcome the impasse. Specifically, since Mechanics EBS visualizes the motion of an object in response to a force input to the object, it may not be able to effectively visualize complex tasks where many forces act on an object, thus prohibiting the learner from solving the problem.

In this study, an impasse is defined as a state in which similar failures over a long period of time during the trial-and-error process prohibit the learner from making any progress in solving a problem. It is common practice to give a learner who is stuck a clue pertaining to their error or to outright give them the correct answer (Shute, 2008). However, giving the correct answer interferes with the trial-and-error process that EBS is centered around.

Yamamoto et al. (2021) used a simple electroencephalograph to estimate the learner's stuck state for problem posing in arithmetic, identified the cause of the stuck state based on an analysis of the learning task, and provided the corresponding feedback, thereby helping to resolve the learner's difficulties. The research indicates the need for domain-specific feedback to assist with learners' impasse.

Providing auxiliary problems that help learners to understand the original one might be an effective method for encouraging students to continue the trial-and-error process without giving them the correct answer. One way to create auxiliary problems is to simplify the original problem (Hirashima et al., 1994). Students can use what they learn from solving these simplified problems to help them solve the original problem.

In our study, we developed an EBS system for mechanics that automatically diagnoses the learner's error points and presents auxiliary problems accordingly. Specifically, we designed a system that implements conventional EBS by designing both auxiliary problems and their problem sequences and that analyzes error points based on the learner's answer history. We evaluated this system by conducting an experiment with university students and were able to confirm its effectiveness (Aikawa et al., 2020).

However, elementary mechanics is a junior high school subject in Japan. To extend the applicability of our developed system to beginners, it is important to investigate whether our system was also effective for junior high school students. Therefore, we conducted a class practice session using the system developed in this study.

2. System Used for Classroom Practice

In this section, we provide more details about the system we used in the classroom practice session.

Learners first work on exercises in a system that is similar to conventional EBS (Figures 1(a) and (b)). If they make a mistake on the same problem a certain number of times, then the system offers them the option to solve an auxiliary problem (Figure 1(c)). And if the learner chooses to solve the auxiliary problem, then the system automatically presents them with one (Figure 1(d)). When selecting which auxiliary problem to present to the learner, the system looks at the learner's answer history and analyzes their error points. It then selects an auxiliary problem that is appropriate for that error.

The learner then works on the given auxiliary problem, and if they get it wrong a certain number of times, the system will use a similar procedure to give them an additional one. If the learner answers a given auxiliary problem correctly, then the system will gradually present more difficult problems from the auxiliary problem list. The goal is for the learner to eventually be able to solve the original problem.

To develop this system, we needed a set of auxiliary problems appropriate for the treatment of each error point, as well as a series of problems organized based on the differences between them. We designed and implemented several auxiliary problems and their problem sequences in EBS.

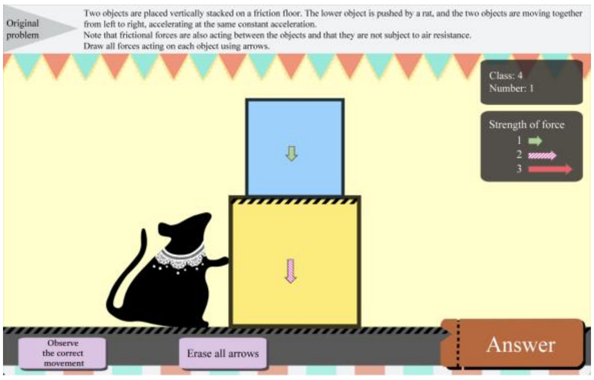
This system was implemented on a tablet. By implementing it in this way, we were able to make adjustments that made it easier for junior high school students to input data, a conclusion based on the opinions of those who had to experience teaching with the system. In this system, learners are first presented with a target problem, which they work on.

2.1 Auxiliary Problems

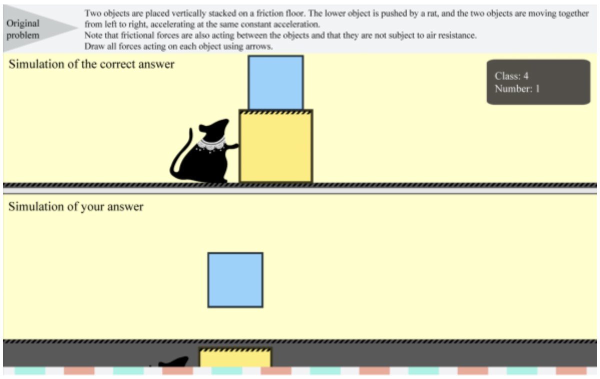
This section describes the auxiliary problems handled by the system. Figure 2 shows all the problems implemented in the system and their problem sequence.

We created auxiliary problems to help learners learn each of the forces in the original that were missing in their answers. The base of the auxiliary problems in this sequence is the "Original problem" shown in Figure 2. In it, two objects are placed on top of each other on a floor, and the lower object is pushed sideways by an external force, causing it to accelerate. There are nine forces at work in this problem that is categorized by the element, such as gravity, vertical drag, and so on. In this example, forces X and P are gravity, forces W and R are vertical drag forces, force S is the force exerted by the upper object on the lower object, force T is the applied external force, and forces V, Q, and H are friction forces.

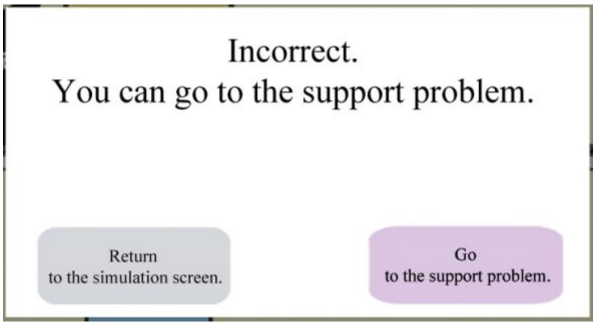
Auxiliary problems were then created for each of these elements so that the learner's attention could be drawn to specific ones by solving the problems related to them. This system implements a series of eight problems, including the seven auxiliary problems created in this way and the original problem.



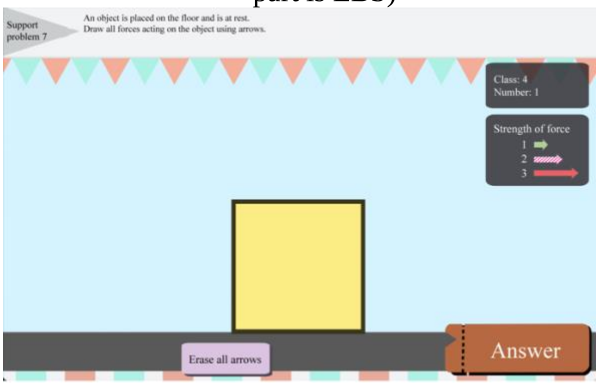
(a) Original problem presentation screen.



(b) The simulation screen presenting the solution in (a). (Upper part is correct simulation, lower part is EBS)



(c) Selection screen for auxiliary problem presentation.



(d) Support problem 7 presentation screen.

Figure 1. System screen.

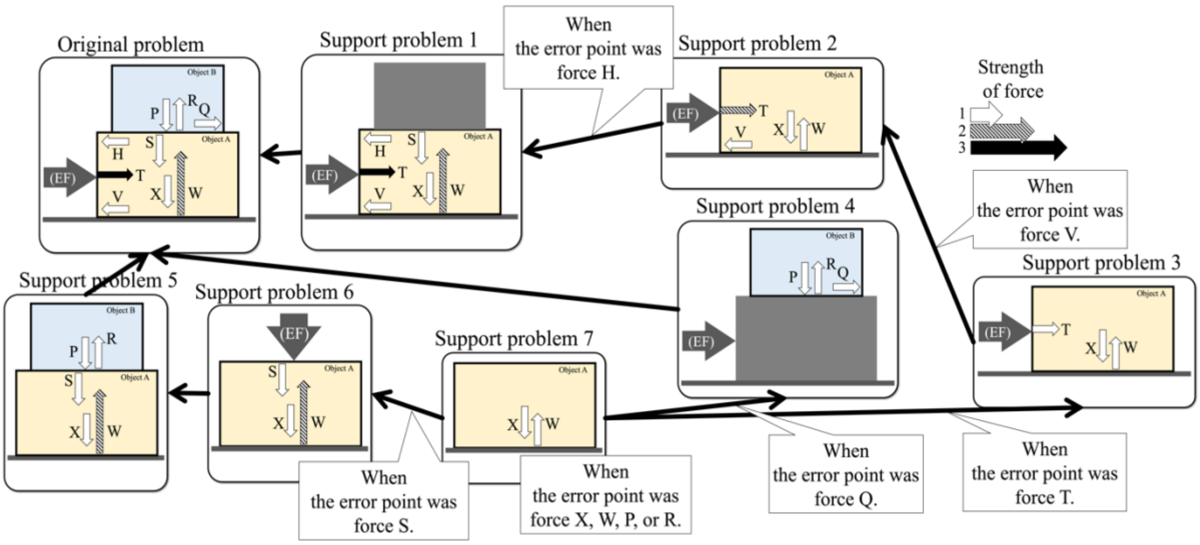


Figure 2. Problem sequence implemented in the system.

2.2 Analysis of Error Points

This section describes the method used by this system to analyze the learner's error point. Since our definition of impasse involves repeatedly making similar mistakes over a long period of time. We have the system look at the learner's answer history and analyze the error point by counting the occurrences of the most frequent errors.

Specifically, the system compares the forces represented in the learner's drawing as an answer with those in the correct answer and counts how many are missing. For example, for the original problem in Figure 2, the acting forces include gravity, vertical drag, a frictional force, the force exerted by the upper object on the lower one, and the applied external force. If the learner's answer omits the force S, diagnosed as "the learner missed the force exerted by the upper object on the lower object."

The system performs this kind of analysis for each answer given by the learner and extracts the forces that are excluded the most often in the learner's answer history. It then uses the most frequently missed as the learner's error point. For example, if a learner gives a solution five times and misses force S four times, force Q three times, and force W once, the system counts them and assumes that the force S missed most frequently is the error point.

When multiple forces are tied for the highest omission count, which is the learner's error point, then each of them is assigned a priority in advance, and the auxiliary problem corresponding to the one with the higher priority is presented. This priority was set in such a way as to eliminate conflicts: gravity has the highest priority, followed by the external forces, vertical drag, the force exerted by the upper object on the lower object, and the frictional forces.

2.3 Auxiliary Problem Presentation

In this section, we describe how the system presents auxiliary problems. The system compares the learner's error point from Section 2.2 with the problem sequence in Figure 2 and then presents the corresponding auxiliary problem. The problem sequence in Figure 2 shows which auxiliary problem is presented when a force is missing, and which auxiliary problem is to be worked on next if the correct answer to the current auxiliary problem is given.

Specifically, the system first presents the original problem. And if the learner answers incorrectly, the system analyzes the error point in the method described in Section 2.2. Next, the system refers to the arrow corresponding to that error point from Figure 2. The system then presents in turn the two auxiliary problems connected by that arrow. If the learner again answers the auxiliary problem incorrectly, the system presents the auxiliary problem corresponding to the error point in the same way. If the learner correctly answers the auxiliary problem, the system returns to the original problem following the arrows in Figure 2.

For example, if the learner continues to make errors about the force S, the system will refer to the arrow "when the error point was force S" in Figure 2. This arrow connects from support problem 7 to support problem 6. Therefore, support problem 7 is presented first, followed by support problem 6. Support Problem 7 is a problem where the object is stationary on the floor. And support problem 6 is a problem in which the top object is removed, and an external force is applied to the bottom object from above. By working on these two auxiliary problems, learners begin to associate the force exerted by the upper object with the one acting downward on the lower object. If the learner correctly answers support problems 6 and 7, the system then presents support problem 5. However, if the learner makes an error on the support problem, the system again analyzes the error point as in Section 2.2 and presents the auxiliary problem, referring to the arrow corresponding to the error point.

The learner works through the aids presented in this way. The system eventually returns to the original problems at the end, at which point the learner is expected to be able to answer them.

3. Classroom Practice and Evaluation

3.1 Overview

Three third-grade classes (29 students per class) at a public junior high school were given a three periods (135 minutes) practice using our system. Classroom practice was conducted in the following order: greetings and explaining classes (41 minutes), a pre-test (10 minutes), learning with the system (64 minutes), and a post-test (10 minutes). At the end of the session, the students completed a questionnaire about the system in 10 minutes. The participants were students aged 14-15 years old; omitting those who were absent, the total number of participants was 81.

Learning effectiveness was evaluated based on the results of the pre-test and the post-test. The test consisted of seven problems, four of which (TP1, TP3, TP4, and TP5) were problems covered by the system (Learning task) and three of which (TP2, TP6, and TP7) were applied problems that were not covered by the system (Complex task). The content of the pretest and posttest were the same, and the maximum score was 7 (1 point per problem). The students' impressions of the system and the auxiliary problems were also analyzed from the questionnaire responses.

3.2 Test Results

The results of the pre-test and the post-test will be discussed. First, the total results show that most students improved their scores through the use of the system, with a mean score (SD) of 0.64 (0.93) on the pre-test and 3.41 (1.05) on the post-test. No student's score declined from the pre-test to the post-test. The t-test results detected a significant difference between the pre-test and the post-test of $p < .001$. Furthermore, the learning task and the complex task shows the mean score (SD) for the pre-test for all four problems was 0.59 (0.81), while the mean score (SD) for the post-test was 3.11 (SD), indicating a significant improvement in performance. On the other hand, performance on complex tasks also improved, with a pre-test of 0.05 (0.22) and a post-test of 0.30 (0.51).

Some of the test problems are shown in Figure 4, and both the number of correct answers per problem and the percentage of correct answers are shown in Figure 3. A problem that was considered too difficult for junior high school students (Figure 4(c)) was implemented as the original problem, and exercises were conducted. However, more than half of the students answered the problems correctly during the class and 32 students answered them correctly on the test, while none answered them correctly on the pre-test. This suggests that even problems that are initially unsolvable can become solvable by using our system. Additionally, 32 out of 81 students correctly answered the most basic problem (Figure 4(a)) in the pre-test, while all 81 students correctly answered it in the post-test.

Furthermore, 69 students were able to answer test problem 4 (Figure 4(b)) correctly on the post-test, compared to only 2 on the pre-test. This suggests that the system can be providing support in solving difficult problems.

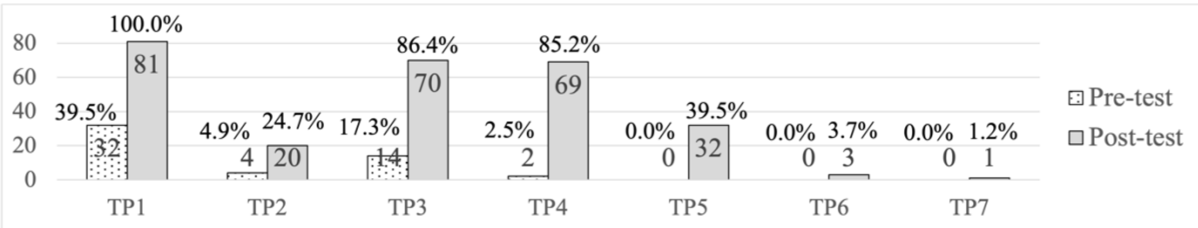
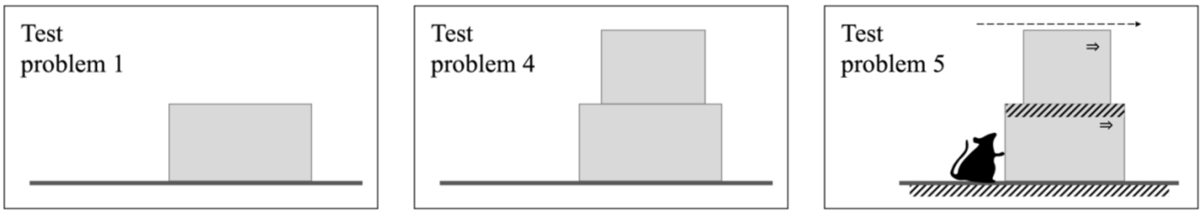


Figure 3. Number of correct answers per test problem (N = 81).



(a) The most basic problems dealt with in this class.

(b) The problem of two objects piled up.

(c) Highly difficult problem.

Figure 4. Problems dealt with in this class.

3.3 Questionnaire Results

The questionnaire was administered using the six-point scale from "1 strongly disagree" to "6 strongly agree," and the average of the responses was calculated. The questions asked were related to the tasks in this study and our system. For the sake of clarity, we refer to this system in this practice session questionnaire as the "app" and to the auxiliary problems as the "support problems."

First, "Do you think learning problems that focus on areas you don't understand will help you to understand them?" was found to receive a high rating of 5.78. Next, "Do you think the support problems presented by the app will help you in comprehending the parts you don't understand?" was found to receive a high rating of 5.46. These results suggest that students felt as though the auxiliary problems helped them to understand the parts they were unfamiliar with. Then, “Did you feel that you were presented with support problems adaptive to your errors?” was found to receive a high rating of 5.11. This result suggests that students feel the support problems adapt their error. And “If you don’t understand a problem, do you think trying to solve a simpler version of it will help you to understand the original problem?” was found to receive a high rating of 5.52. Finally, “Do you think the support problems helped you solve the original problem?” was found to receive a high rating of 5.52. This result suggests that students feel the support problems helped them solve the original problem.

3.4 Discussion

The results of 3.2 and 3.3 suggest that our system has a significant impact on learning. Additionally, materials called “Additional Missions” were handed out to students who completed the exercises during practice time. In total, 61 copies of the additional mission forms were distributed, indicating that 61 of the 81 students had completed the original problem within the time available for the exercise. However, none of the students answered the original problem correctly the first time, suggesting that the system was able to help learners learn to solve the problems they could not solve.

4. Conclusion

In this study, we conducted an evaluation experiment at a junior high school on an EBS system that adaptively presents auxiliary problems to learners who get stuck.

Future work includes analyzing logs and investigating learning activities. In addition, the current problem sequence is manually generated by focusing individually on each force, but in the future, we plan to investigate a method for automatically generating auxiliary problems from the target problems (Aikawa et al., 2021).

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