

Error-Based Simulation for Error-Visualization and Its Management

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Abstract Behavior simulation is an effective method to visualize the meaning of mechanical concepts and has been applied in many computer-aided education systems. These simulations are not useful, however, for a learner who has already formulated an erroneous equation. In order to help the learner to recognize and correct the error, simulating the erroneous equation is a promising method. In this paper, we propose Error-Based Simulation (EBS) which reflects an erroneous equation a learner gave in solving a mechanical problem. We have developed a prototype system which generates EBS by changing the value of "velocity" or "acceleration" of an object by using an erroneous equation. In EBS, the object behaves in a strange manner. The differences between EBS and normal simulation illustrate the error clearly. EBS, however, is not always effective for a learner to recognize and correct an error. The effect depends on how strange it behaves. Therefore, diagnosing the behavior of EBS is very important to use it adequately. In this paper, we also describe a framework for managing EBS with qualitative reasoning techniques.

INTRODUCTION

Understanding physical phenomenon by using physical concepts and laws is a primary goal of physics education. The concepts and laws, however, are often too abstract to be meaningful to learners; thus, the relation of the concepts and laws to physical phenomenon is often not apparent for them. Therefore, to help learners to understand the relation is an important issue of physics education (White 1993a). Behavior simulation is an effective method in describing semantics of physical concepts and laws, and has been applied in many tutoring systems for teaching physics (Tiberghien & Mandl 1991; White 1993b; Thomas 1995). These simulations are useful when a learner expects different behaviors or can not expect any behaviors. However, a learner often makes a mistake on the learning of physics even if the learner knows the correct behavior. For such a learner, it is not enough only to provide the correct simulation. In order to help the learner to recognize and correct the mistake, generating a simulation which reflects the mistake is a promising method.

In this paper, we propose Error-Based Simulation (EBS): this reflects an error in a motion equation a learner gave in solving a mechanical problem. We have developed a prototype system which generates EBS by changing the value of "velocity" or "acceleration" of an object by using an erroneous equation (Hirashima, Noda, Kashihara & Toyoda 1995a). In the EBS, the object behaves in a strange manner. The differences between EBS and normal simulation illustrate the error clearly.

The authors, however, have confirmed that EBS isn't always effective for a learner to recognize and correct erroneous equations through experiments (Hirashima, Horiguchi, Kashihara & Toyoda 1995b). In the experiments, learners who formulated erroneous equations were shown EBS for their erroneous equations. In the results, when differences between EBS and a normal simulation weren't qualitative ones in "velocity" or "acceleration," a learner often

could not judge which behavior was correct. In order for EBS to be effective, EBS should have such qualitative differences from a normal simulation. Therefore, it is very important to diagnose the differences between EBS and a normal simulation.

In this paper, a framework for managing EBS with qualitative reasoning techniques is also described (Hirashima, Horiguchi Kashihara & Toyoda 1997). First, by using qualitative simulation (Kuipers 1994), the behavior of EBS is predicted. It is compared with the behavior of a normal simulation, similarly predicted by using qualitative simulation. When a qualitative difference is found, EBS is effective for error-visualization. When qualitative differences aren't found, a parameter whose perturbation causes qualitative differences between EBS and a normal simulation is sought by using comparative analysis (Weld 1988). This qualitative difference is also useful for error-visualization. If such a parameter cannot be found, EBS shouldn't be used for error-visualization. Currently, a module which realizes the above management of EBS has been implemented. The module is called EBS-manager. This paper also discusses the effectiveness of EBS-manager through experiments.

ERROR-BASED SIMULATION

Framework of EBS

In traditional curricula in physics, learners are first presented with abstract formulae, for example, " $V=IR$ " and " $F=ma$." The learners often find it very difficult to map such abstract formulae to the physical-world (Laurillard 1993; White 1993b). Therefore, the learners often formulate erroneous equations without really understanding the meaning of them, and cannot understand why and how they erred. For such cases, telling the learners the correct answers is not enough to prevent the same mistakes from recurring (VanLehn, Jones & Chi 1992; Maybury 1993). Simulating the erroneous equation is a promising method to illustrate the error. However, not much research has been carried out in studying how to realize the simulation.

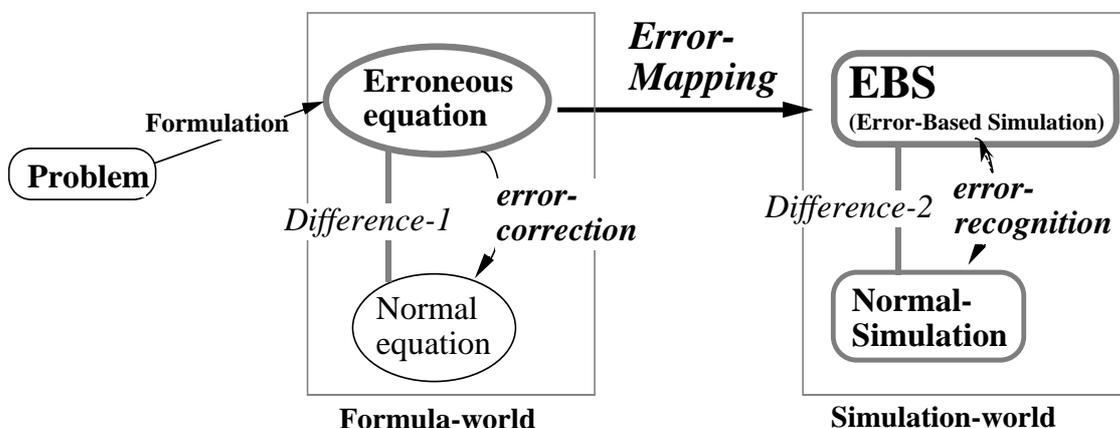


Figure 1. Framework of Error-Visualization with EBS (Error-Based Simulation).

Figure 1 shows the framework of error-visualization by EBS. EBS is generated by mapping an erroneous equation in formula-world to simulation-world. The EBS shows irregular behavior in contrast with the behavior of a normal simulation. The differences motivate a learner to correct the error and provide useful information to do so.

Error-Mapping

The method which reflects an erroneous equation onto the behavior simulation is called "error-mapping." A mechanical component which can be set up as an equation of motion, such as a block, slope and platform-car, is called an "object." Each object is given several equations constraining its mechanical attributes and behavior. These equations allow us to generate the

normal simulation. Currently, the error-mapping changes a value of a "velocity" or "acceleration" of an object by using the erroneous equation, and then generates EBS with the changed value. Therefore, in the simulation, an object behaves in a strange manner and other objects behave normally.

The procedure to generate EBS is divided as follows: (1) specifying an object to change the behavior (this object is called the ER-object); (2) specifying an attribute to change its value for reflecting the erroneous equation (this attribute is called the ER-attribute); (3) deriving the changed value (this value is called the ER-value). When the dimensions of the unit system in the erroneous equation are wrong, it is impossible to calculate the ER-value. Therefore, the coordination of the unit system in the erroneous equation is indispensable to generate EBS. The following is a short description of the elements.

ER-object: Currently, the error-mapping method changes the behavior of only one object at a time. If the erroneous equation is related only to an object, the object is selected as ER-object. When the equation relates to multiple objects, an object included in an erroneous term is selected. Then, other objects' behaviors are simulated normally. However, several components in mechanical problems that no equation of motion is set up for, such as strings, sometimes move in irregular ways following the ER-object. For example, a string is dealt with as a connection between objects, not as an object, and moves to keep the relation between the two objects. When the object, which is connected to a string, is selected as ER-object, the string moves in an irregular way following the object. When the ER-object is moving faster than in normal behavior, the string connecting to the ER-object is shortening or lengthening following the movement of the ER-object. Moreover, the outline of each object is not considered in the simulation. To keep the outlines, every object is required to move normally. Therefore, the ER-object behaving in a strange manner sometimes sinks into another object. Consequently, irregularity and unnatural behavior of the ER-object are exaggerated.

ER-Attribute and ER-value: "Velocity" and "acceleration" are essential attributes in behavior simulation. Changing them is the most effective way to reflect erroneous equations in a simulation. If the error occurs in the velocity or acceleration part, the erroneous expression in that part is used to calculate the velocity or acceleration directly. If the part of velocity and acceleration is normal, normal values are substituted in place of variables except for the velocity or acceleration part. Then the ER-value is calculated by using the erroneous equation and the normal values. The set of normal values is prepared for each problem beforehand. When both velocity and acceleration exist in the equation, velocity is preferred.

Examples of EBS

This section describes some examples of EBS using Problem-1 shown in Figure 2. Problem-1 is a three-blocks problem with one pulley. Each object is given several equations constraining its physical attributes and behavior. Problem-1 requires learners to set up the four equations of motion shown in Figure 2. These equations allow us to generate a normal simulation.

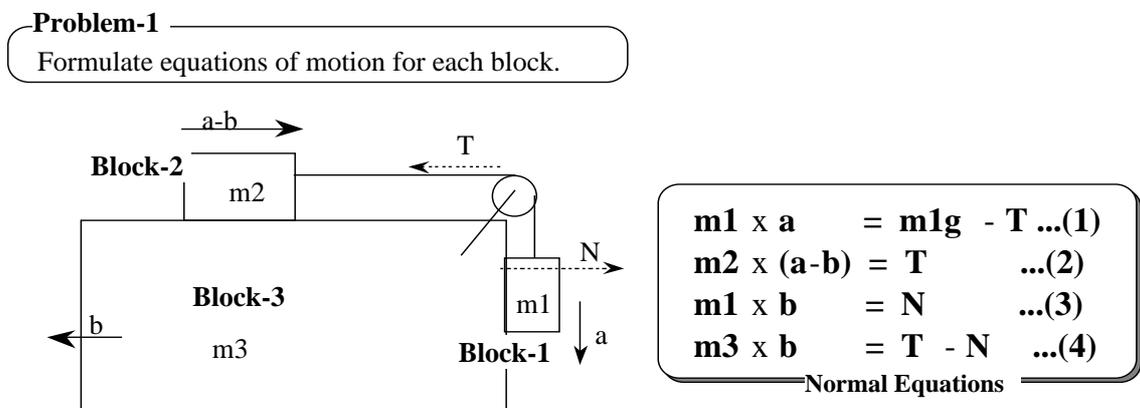


Figure 2. An example of mechanical problem and correct answer consisting of four equations.

Here, the mass of Block-1 is “m1,” Block-2 “m2” and Block-3 “m3.” Assume that the mass of the pulley and string are zero. Each block can move without friction. Block-1 is restricted to move along the side of Block-3. Therefore, reactionary force exists between Block-1 and Block-3, and then the two blocks move as one towards the left. Because Block-3 moves, relative acceleration should be used in the equation of motion of Block-1. The vertical component of acceleration of Block-1 is “a.” The horizontal component of acceleration of Block-3 is “b.” The horizontal component of acceleration of Block-2 is “a-b.” T is the tension of the string between Block-1 and Block-2. N is the reactionary force between Block-1 and Block-3.

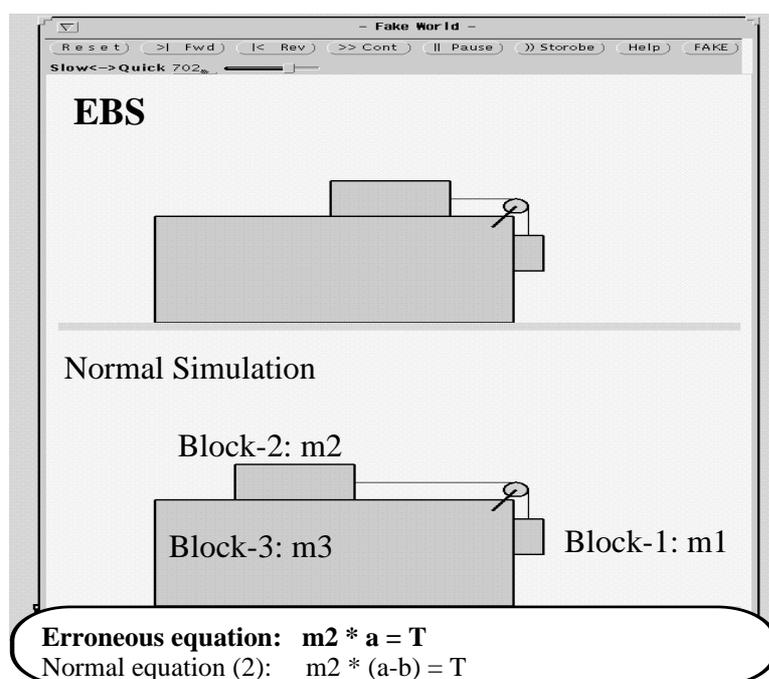


Figure 3. An example of EBS (1).

Learners sometimes formulate the erroneous equation, " $m_2 \cdot a = T$," instead of the normal equation " $m_2 \cdot (a-b) = T$." Figure 3 shows the EBS for this erroneous equation. Because the equation corresponds to horizontal-motion of Block-2, the ER-object is Block-2. Since the error occurs in the acceleration part, the ER-attribute is acceleration. Therefore, the ER-value is calculated with the erroneous acceleration part. In this case, the value of "a" is the ER-value directly. The ER-value "a" is larger than the normal value "a-b." Therefore, Block-2 in the EBS moves faster than in the normal simulation. Because Block-1 moves with normal acceleration in spite of the irregular movement of Block-2, the distance between Block-2 and Block-1 is being narrowed. As a result, the string is shortening. Currently, our prototype system generates both the EBS and normal simulation shown in Figure 3. The upper simulation is the EBS and the lower one is the normal simulation. Therefore, learners can compare the two simulations easily.

Figure 4 shows the EBS for the erroneous equation " $m_3 \cdot b = -N$ " corresponding to the normal equation " $m_3 \cdot b = T - N$." The ER-object is Block-3 and the ER-attribute "acceleration." Since the acceleration part of the equation is normal, the ER-value is calculated by substituting normal values in each variable except for the ER-attribute, that is, "m3" and "N." The sign of acceleration which is the ER-attribute is changed. So, Block-1 moves toward the left normally, but Block-3 moves toward the right erroneously. Consequently, Block-1 sinks into Block-3.

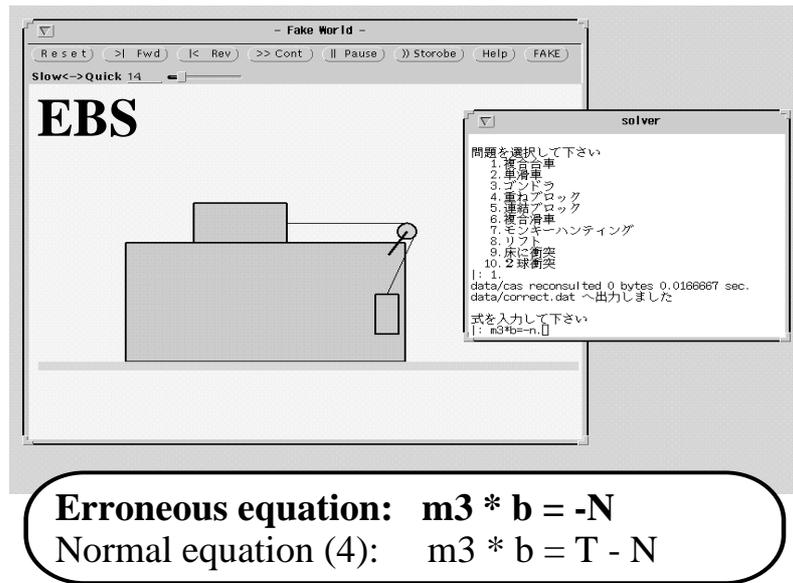


Figure 4. An example of EBS (2).

Figure 5 shows the EBS for the erroneous equation " $m_3 * b = T$ " corresponding to the normal equation " $m_3 * b = T - N$." The ER-object is Block-3 and the ER-attribute "acceleration." Since the acceleration part of the erroneous equation is normal, the ER-value is calculated by substituting normal values in each variable except for the ER-attribute. The acceleration in the EBS is larger than in the normal simulation. So, Block-3 moves toward the left faster than in normal simulation. Then Block-1 moves normally. Therefore, Block-3 moves faster than Block-1. Consequently, Block-1 is separated from Block-3.

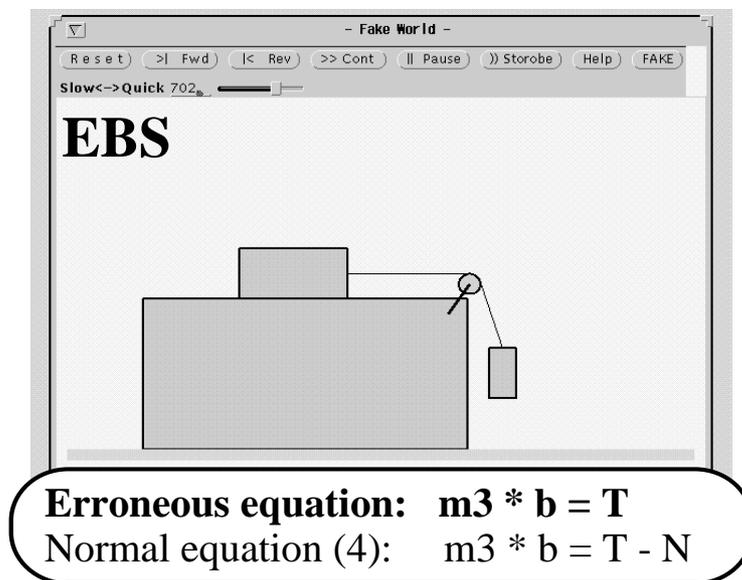


Figure 5. An example of EBS (3).

As a preliminary evaluation, the problem shown in Figure 2 was given to six college students belonging to the department of engineering and they were asked to solve it. They used the EBS and normal simulation for each equation they formulated. The total number of erroneous equations they generated was fifteen. All of the students reported EBS was useful to recognize their errors themselves and motivated them to correct the errors. For nine errors, students could correct the errors themselves with EBS. This result suggests that EBS is effective

to correct these erroneous equations. However, for other problems and errors, EBS doesn't always visualize an error clearly. Therefore, a function to manage EBS is required.

MANAGEMENT OF EBS

Requirement for EBS-manager

The procedure to generate EBS doesn't pay attention to what kind of difference EBS has from a normal simulation. So, EBSs which aren't useful to visualize errors in erroneous equations are sometimes generated. In Figure 6, when a learner set up Equation-B as an equation of motion of the Block, EBS based on Equation-B shows the Block ascending the Slope, while the normal simulation based on Equation-A shows the Block descending the Slope. In this case, EBS visualizes the error clearly. When a learner set up Equation-C, EBS based on Equation-C only shows the Block moving in the same direction as the normal simulation along the Slope as a little different velocity and acceleration. In this case, it is difficult for the learner to judge which behavior is correct. So, for Equation-C, EBS shouldn't be used directly. However, when the angle of the Slope θ increases, velocity and acceleration in EBS decrease while ones in a normal simulation increase. Such strange changes in behavior enable the learner to recognize the error.

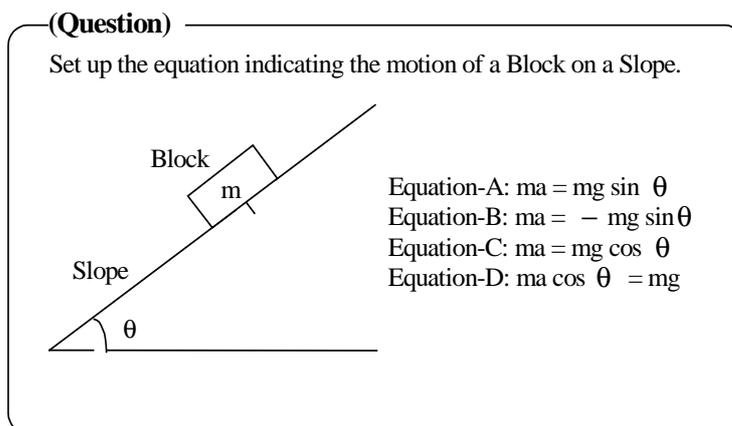


Figure 6. An example of mechanics problem.

Through these examples, in order to visualize an erroneous equation clearly by EBS, we assumed that EBS should include qualitative differences in "velocity" or "acceleration" against normal simulation. Based on this assumption, an EBS-manager is required as follows:

1. EBS-manager can analyze the behavior of both EBS and a normal simulation qualitatively and judge whether there is a qualitative difference in velocity or acceleration between them or not.
2. When there isn't any qualitative difference, the EBS-manager can search for a parameter whose perturbation causes a qualitative difference in velocity or acceleration between EBS and a normal simulation.

Qualitative reasoning techniques are used to realize the EBS-manager. Before explaining its mechanism in detail, "qualitative differences" which contribute to recognizing errors are defined as follows:

Definition-1: There is a "qualitative difference" between two objects' behaviors when the qualitative values, e.g., "plus," "zero" and "minus," of velocity or acceleration of the objects are different. For example, in Figure 6, the qualitative values of the velocity and acceleration of the ascending Block in the EBS based on Equation-B are "minus," while the qualitative values of the velocity or acceleration of the descending Block in the normal simulation based on

Equation-A are "plus." Therefore, there is "qualitative difference" between the EBS based on Equation-B and the normal simulation based on Equation-A.

Definition-2: There is a "qualitative difference" between two objects' changes in behaviors when the qualitative values, e.g., "increasing," "steady" and "decreasing," of the ratio of their velocity's or acceleration's change to a parameter's (except time) change are different. The qualitative values are called "qualitative directions." For example, in Figure 6, the velocity or acceleration of Block in EBS based on Equation-A increase when the Angle of the Slope \emptyset increases. Therefore, the qualitative directions of the velocity and acceleration are "increasing." The velocity and acceleration of Block in EBS based on Equation-C decrease when the Angle of the Slope \emptyset increases. Therefore, the qualitative direction of the velocity and acceleration are "decreasing." So, there is "qualitative difference" between the EBS based on Equation-C and the normal simulation based on Equation-A when the Angle of the Slope changes.

Mechanism of EBS-manager

The error management procedure of the EBS-manager is divided into two phases. In Phase-1, the EBS-manager compares the qualitative behavior of the EBS with that of a normal simulation. When a qualitative difference is found, the EBS-manager judges that the EBS is effective for error-visualization and shows the EBS to a learner. When a qualitative difference cannot be found, it proceeds to Phase-2. In Phase-2, the EBS-manager tries to find a parameter the perturbation of which causes a qualitative difference between the EBS and a normal simulation. When such a parameter cannot be found, the EBS-manager judges that the EBS shouldn't be used to visualize the error.

Phase-1: qualitative simulation

First, the EBS-manager predicts qualitative behavior of the EBS by using qualitative simulation and compares it with the qualitative behavior of a normal simulation similarly predicted by qualitative simulation. When a qualitative difference is found, the EBS-manager judges that the EBS is effective for error-visualization.

By using QSIM (Kuipers 1994), the EBS-manager derives the sequence of qualitative states based on an erroneous equation and similarly derives the sequence of qualitative states based on a normal equation. The qualitative state (it is called QS) consists of "qualitative value of velocity" and "qualitative value of acceleration." The sequence of QSs is described as $\{QS_1, \dots, QS_n\}$. Let $\{QS_1, \dots, QS_n\}$ be the sequence of QSs based on an erroneous equation and let $\{QS_1', \dots, QS_n'\}$ be the sequence of QSs based on a normal equation. Then the EBS-manager compares both sequences and searches for the interval in which QSi has a qualitative difference from QSi' (in the sense of Definition 1). When such an interval is found, the EBS corresponding to the interval is used to visualize the error.

Note that if there are several intervals in which QSi has qualitative difference from QSi' , it is necessary to judge which interval is the most effective for error-visualization. The most effective interval means the interval in which QSi has the most effective qualitative difference from QSi' . Currently, the EBS-manager places a higher priority on velocity than acceleration. It is a kind of empirical rule. In general, it is a difficult problem to judge which qualitative difference is the most effective for a learner to recognize the error. This issue is an important one for future work.

For example, in Figure 7 (initial velocity is added to the problem in Figure 6), there are two intervals in which the EBS based on Equation-B has qualitative differences from a normal simulation based on Equation-A. In Interval-1 (I1), the EBS has a qualitative difference only in acceleration. However, in Interval-2 (I2), the EBS has qualitative differences in velocity and acceleration. Therefore, the EBS-manager judges that Interval-2 is more effective for error-visualization than Interval-1. In this case, the EBS-manager is sometimes required to adjust parameters to show Interval-2. For example, in Figure 7, if the length of the Slope (x_0) is too short or initial velocity (v_0) is too large, the Block in the EBS doesn't behave according to the

sequence of qualitative states that contains Interval-2 because the location of the Block comes to zero before the velocity of the Block comes to zero. (Transition of location occurs before the one of velocity occurs.) Therefore, the EBS-manager should adjust the parameter x_0 or v_0 in order for the Block in the EBS to behave according to the sequence of qualitative states that contains Interval-2. Since QSIM cannot treat such a parameter adjustment, formulation of the method of the parameter adjustment is one of the most important issues.

Equation-A: $ma = mg \sin \theta$
 (Initial Velocity $v_0 > 0$)

Equation-B: $ma = - mg \sin \theta$
 (Initial Velocity $v_0 > 0$)

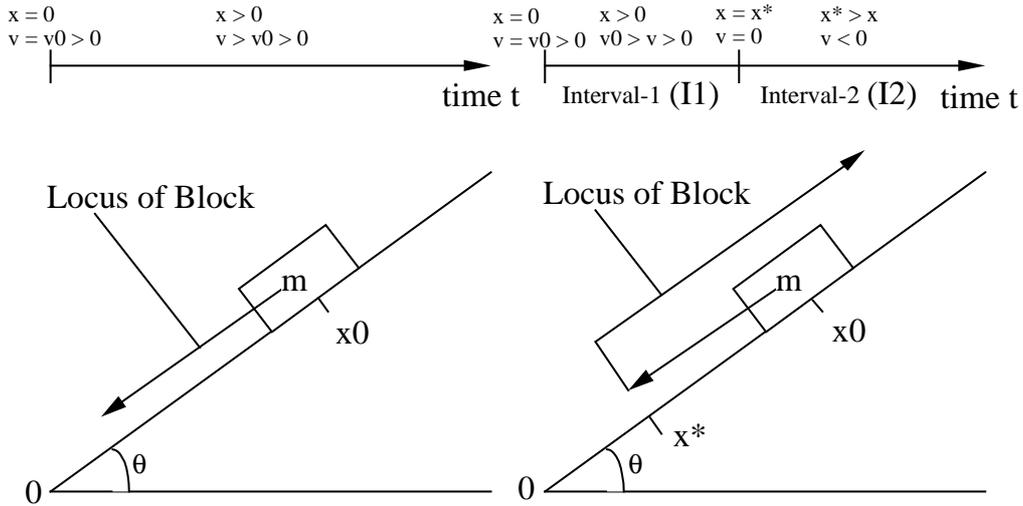


Figure 7. The interval in which EBS has qualitative differences from a normal simulation.

Phase-2: comparative analysis

When a qualitative difference cannot be found, the EBS-manager tries to find a parameter by using comparative analysis the perturbation of which causes a qualitative difference between the EBS and a normal simulation. When such a parameter cannot be found, the EBS-manager judges that the EBS shouldn't be used to visualize the error.

After deriving the sequence of qualitative states based on an erroneous equation by QSIM, the EBS-manager derives the sequence of qualitative directions corresponding to the sequence of qualitative states with perturbation of a parameter by using DQ analysis (Weld 1988). It similarly derives the sequence of qualitative directions with perturbation of the same parameter based on a normal equation. For one qualitative state, two types of qualitative directions are derived, one is "qualitative value of the ratio of velocity's change to a parameter's (except time) change" and the other is "qualitative value of the ratio of acceleration's change to a parameter's (except time) change." The pair of them for QS is called QD. The sequence of QDs is described as $\{QD_1, \dots, QD_n\}$. Let $\{QD_1, \dots, QD_n\}$ be the sequence of QDs based on an erroneous equation and let $\{QD_1', \dots, QD_n'\}$ be the sequence of QDs based on a normal equation. Then the EBS-manager compares both sequences and searches for the interval in which QD_i has qualitative difference from QD_i' (in the sense of Definition 2). When such an interval cannot be found with the perturbation of a parameter, the EBS-manager runs the same process with the perturbation of another parameter. When such a parameter and interval are found, the EBS corresponding to the parameter and interval is used to visualize the error.

For example, in Figure 8 (the same problem as Figure 6), for Equation-C, the EBS-manager cannot find any qualitative difference between the EBS based on Equation-C and a normal simulation based on Equation-A by qualitative simulation. In this case, by using

comparative analysis, θ is found as a parameter the perturbation of which causes qualitative difference between the EBS based on Equation-C and a normal simulation based on Equation-A. Increasing θ increases acceleration of the Block in the normal simulation, while increasing θ decreases acceleration of the Block in the EBS.

Equation-A: $ma = mg \sin \theta$	Equation-C: $ma = mg \cos \theta$
When θ increases: v increases a increases	When θ increases: v decreases a decreases

(Length of arrows indicates the magnitude of velocity and acceleration.)

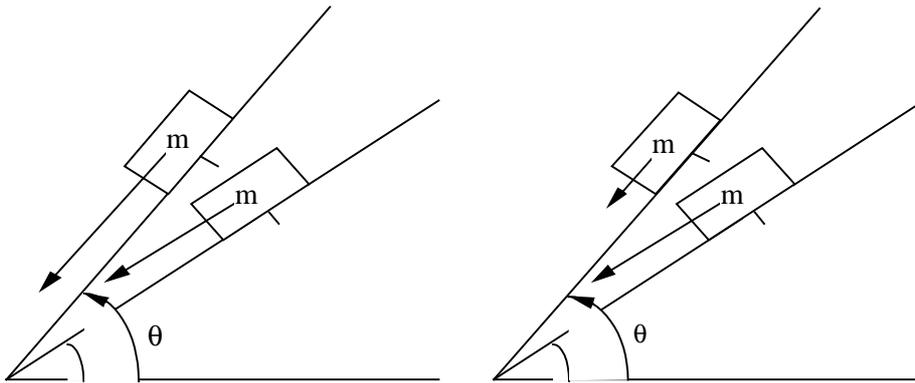


Figure 8. The parameter whose perturbation causes a qualitative difference.

Note that if there are several parameters whose perturbation causes qualitative difference between the EBS and a normal simulation or if there are several intervals in which QDi has a qualitative difference from QDi' , it is necessary to judge which parameter or interval is the most effective for error-visualization. The most effective parameter means the parameter whose perturbation causes the most effective qualitative difference between QDi and QDi' , and the most effective interval means the interval in which QDi has the most effective qualitative difference from QDi' . Currently, the EBS-manager prefers a change of velocity over one of acceleration. It is also a kind of empirical rule.

For Equation-D, the EBS-manager cannot find any qualitative difference between the EBS based on Equation-D and the normal simulation based on Equation-A by qualitative simulation. Moreover, in spite of comparative analysis, no parameter is found whose perturbation causes qualitative difference between the EBS based on Equation-D and a normal simulation based on Equation-A. In such a case, the EBS-manager judges that the EBS shouldn't be used to visualize the error. The way to treat this case is discussed in the next section.

PRELIMINARY EVALUATION

The EBS-manager has been developed on Sun SPARCstation10 with Japanese Open Windows Ver.2.0.1 and Lucid Common Lisp and its effectiveness evaluated through a preliminary experiment. Using the problem shown in Figure 6 as an example, EBSs which were generated and managed by the EBS-generator and the EBS-manager based on the erroneous equations (Equation-B, Equation-C, Equation-D) were shown to ten subjects who were college students in engineering department. In each EBS case, the subjects were shown both the EBS and a normal simulation at the same time and were asked (1) whether they could judge which behavior was correct, and (2) whether they thought the EBS was useful to understand an error. Figure 9 is a snapshot of simulations shown to the subjects where the EBS and a normal simulation are

shown at the same time. The upper simulation is the EBS based on Equation-B. The lower simulation is the normal simulation based on Equation-A.

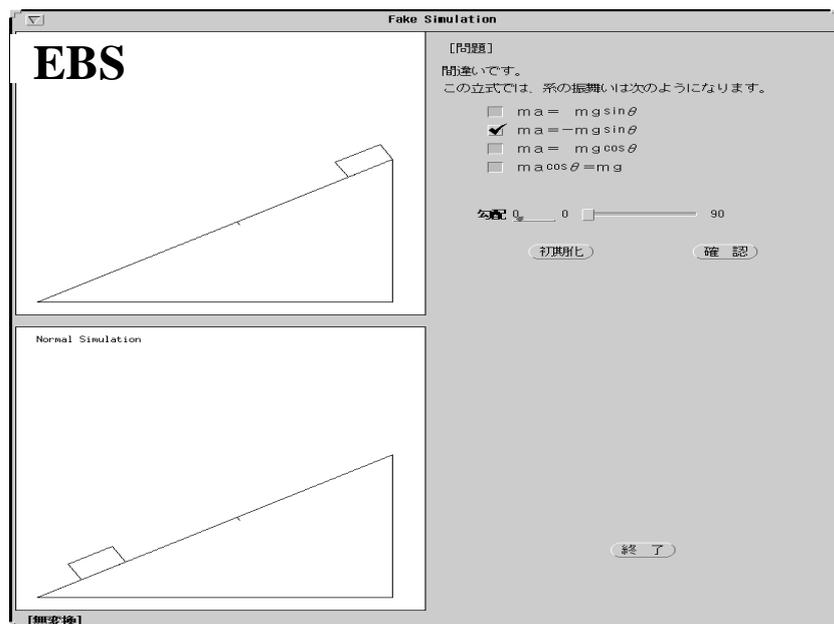


Figure 9. A snapshot of EBS and a normal-simulation.

In the case of Equation-B, by qualitative simulation, the EBS-manager judges that the EBS is effective because it has qualitative differences from a normal simulation based on Equation-A. Therefore, the EBS-manager shows the actual EBS to the subjects. Observing the EBS in which the Block was ascending the Slope, all of them recognized the strangeness in the EBS and could judge which behavior was correct. They also answered that this EBS was useful to understand the error. Therefore, in this case, this result suggests that the EBS is useful to help a learner understand his/her erroneous equation.

In the case of Equation-C, by qualitative simulation, the EBS-manager judges the EBS generated by the EBS-generator is not effective because it does not have any qualitative difference from a normal simulation based on Equation-A. Then, by comparative analysis, the EBS-manager finds \emptyset as the parameter whose perturbation causes a qualitative difference between the EBS and a normal simulation. Therefore, the EBS-manager instructs the subjects to change the \emptyset by direct manipulation, and generates the EBS and the normal simulation with the changed \emptyset . Observing the EBS in which increasing \emptyset decreases acceleration of the Block, all of them recognized its strangeness and could judge which behavior was correct. Eight of them answered that this EBS was useful in understanding an error. Two of them who answered that the EBS wasn't useful, indicated that the interface of the system should be improved to show the two EBSs, one being the original EBS and the other being the EBS with changed \emptyset , at the same time. Even these two said the idea is useful. These results suggest that the modified EBS is a promising method to help a learner correct his/her erroneous equation.

For comparison, the original EBS based on Equation-C with fixed \emptyset was shown to the subjects and all of them could not judge which behavior was correct. They answered that this EBS wasn't useful in understanding an error. This fact indicates the importance of the EBS-manager.

In the case of Equation-D, the EBS-manager cannot find any qualitative difference either by using qualitative simulation or by using comparative analysis. Therefore, currently, the EBS-manager judges that the EBS isn't useful to visualize the error in Equation-D. The subjects were asked whether they had any suggestions in such a case and three of them indicated that changing the \emptyset down to zero (means Flat Floor) or up to 90 degrees (means Vertical Wall) causes a qualitative difference. When \emptyset becomes zero, the Block still moves at gravity

acceleration in the EBS based on Equation-D, while the Block doesn't move any longer in a normal simulation based on Equation-A. When θ becomes 90 degrees, the Block falls down at infinite acceleration in the EBS based on Equation-D, while the Block falls down at gravity acceleration in a normal simulation based on Equation-A. These are qualitative differences, certainly. However, like these cases, changing a parameter to its limit cannot be treated by EBS-manager because DQ analysis treats only perturbations that do not cause any changes in behavioral topology. Improving EBS-manager in order to be able to treat such cases is necessary.

In the evaluation, the subjects were not learners. They evaluated EBS-manager from a teacher's point of view. Beside, only one problem was examined. The above evaluations are not very extensive, but are sufficient to indicate that our approach has promise. More rigorous experiment is required to discuss EBS in more detail. We plan to carry out experimental evaluation by real learners where several problems will be provided to the learners.

RELATED WORK

Interactive Simulation Environments (ISE) for education usually have the ability to visualize errors. The framework of most ISE, though, is different from EBS. In the framework, the errors are visualized by showing a phenomenon which is different from a learner's erroneous prediction. The framework of this method is illustrated in Figure 10.

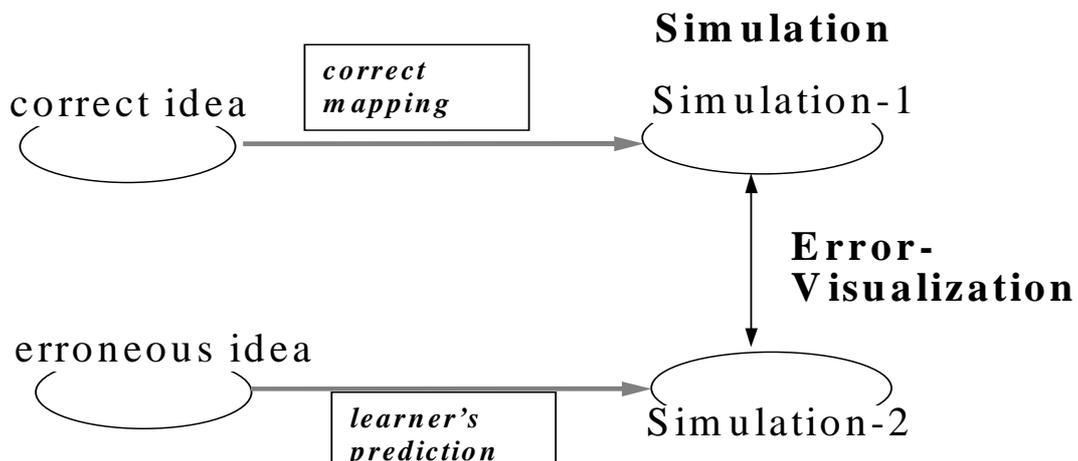


Figure 10. Error-Visualization by Correct Mapping.

In the framework, it is assumed that when the learner has an erroneous idea, she/he predicts an erroneous phenomenon reflecting that idea. Based on this assumption, to show the correct phenomenon, it is useful to visualize the error. When the learner thinks the difference is important between the correct phenomenon and the erroneous one, which is predicted by her/him, she/he is motivated to correct the error. We call this method "Error-Visualization by Correct-Mapping."

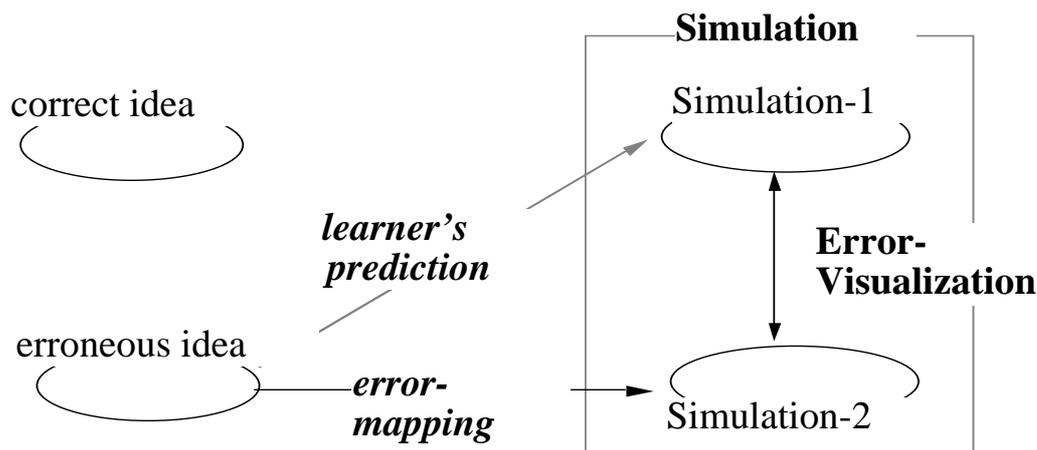


Figure 11. Error-Visualization by Error-Mapping.

The above method is effective when a learner predicts an erroneous phenomenon. A learner, however, does not always predict an inaccurate phenomenon when she/he has an inaccurate idea. The learner often knows a correct phenomenon in spite of her/his erroneous idea. For example, in Dynaturtle (diSessa & Andrea 1982), a learner operates “turtle” and tries to move it following her/his prediction. When the learner has an erroneous idea, she/he fails to control it. The differences between the correct phenomenon, which is predicted by her/him, and the generated phenomenon by operations, often visualize the error. The framework of this method is illustrated in Figure 11. We call this method “Error-Visualization by Error-Mapping.” Several training environments with simulation, for example, STEAMER (Wenger 87), use this method for error-visualization.

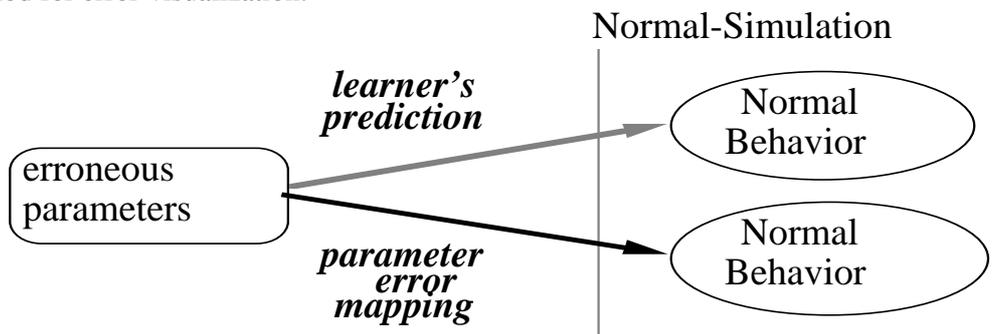


Figure 12. Parameter-Error-Mapping.

Most learning environments using error-mapping, however, only deal with errors of parameters. All phenomenon generated in the environments are following correct laws. When a learner puts erroneous parameters in a simulator, she/he is usually presented with unexpected phenomenon. Although the unexpected phenomenon is different from the learner’s expectation, it is correct for the parameters. Therefore, only one correct simulator is required in such learning environments. We call this type of error-mapping “Parameter-Error-Mapping.” The framework is illustrated in Figure 12.

EBS, however, can deal with an erroneous equation of a mechanical problem. In general, an erroneous equation means an error of rules which control phenomenon. With this definition, a specific simulator is required to reflect the erroneous equation to phenomenon. This framework is illustrated in Figure 13. Equations in physics are rules of object behavior. A correct simulator which is developed to generate a simulation using correct rules cannot deal with erroneous equations. We have proposed EBS to generate a simulation reflecting erroneous equations. In other words, in the framework of EBS, rules used to generate behavior are different in a correct simulation. We call this type of error-mapping “Rule-Error-Mapping.”

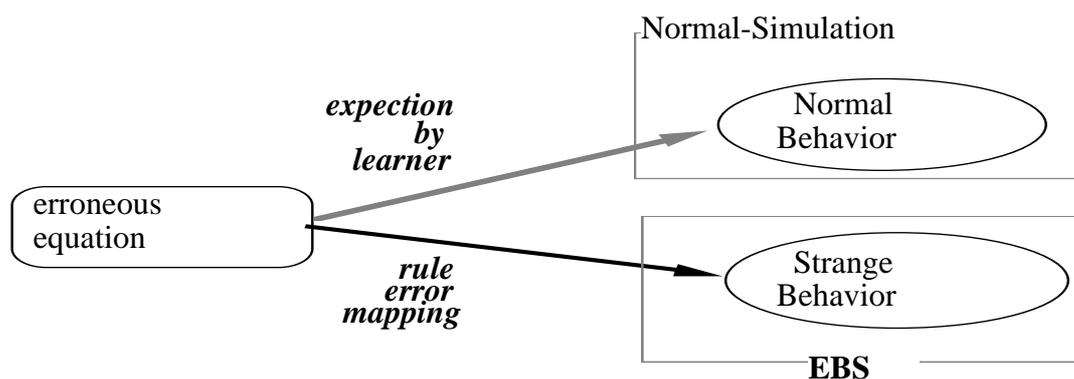


Figure 13. Rule-Error-Mapping.

ARK (Alternate Reality Kit) is a toolkit for creating physical simulations (Smith 1987). Learners can change parameters of objects in the simulation. Therefore, Parameter-Error-Mapping can be realized by using ARK easily. Smith also did a set of tests using ARK to see if learners could identify an accurate simulation among several inaccurate ones. Each learner played in several simulation worlds, but only one was "realistic": the other worlds violated conservation of energy and/or momentum. The results were that students could identify the real world fairly well. The simulation in the other worlds is similar to EBS. However, learners are given the other worlds, but are not required to generate them. Beside, there is no management facility of the simulations.

EBS is a simulation which is impossible in the physical world. A learner, unfortunately, can become confused using EBS. The management of EBS, then, is indispensable. The same situation often occurs following the development of multimedia techniques in human-computer interaction. A user can gather information easily. The importance of quantity of information is decreasing. Conversely, quality of information becomes more important. A promising way to enhance the quality is to emphasize and exaggerate specific parts in the information (Maybury 1993). Such ways also cause the same risk with EBS. Therefore, modification and diagnoses of information, as with EBS and its management, becomes ever more important in realizing human-computer interaction.

Currently, EBS is a function. The ways to use EBS in a learning process or to combine EBS into learning environments are our future work. Joolingen has proposed a framework of simulation-based discovery environments (van Joolingen & de Jong 1996; van Joolingen, King & de Jong 1997). In the framework, assignment is an important instructional support. But, feedback on the answers for the assignment consists of explanation why the answer is right or wrong. EBS may be a promising function to explain why the answer is wrong.

CONCLUDING REMARKS

In this paper, we describe EBS for Error-Visualization and its management. EBS is a method to visualize an erroneous equation in a mechanical problem as a strange behavior. The authors developed EBS-manager to diagnose and modify EBS in order to use EBS effectively. The EBS-manager diagnoses the differences between EBS and a normal simulation by using two qualitative reasoning techniques, that is, qualitative simulation and comparative analysis. The main future work is as follows:

1. To formulate another modification method of EBS: As discussed above, in some cases, changing a parameter to its limit must be considered in order to cause a qualitative difference. It is currently out of the range of the EBS-manager, but checking the lower and upper limits of each parameter quantitatively and interpreting them qualitatively are useful heuristics. To formulate this method is important future work.

2. Error-mapping from behavior prediction to equation: There are several cases in which it is more effective to map an error in behavior prediction to visualize the error. This fact is explained with an example shown in Figure 14. A learner often predicts that a ball released at the left edge of the bowl jumps out of the bowl at the right edge. This is wrong. In this example, it is easier to explain the reason why the predicted behavior is wrong by using an equation. The explanation is as follows: a learner easily understands that the whole energy of the ball at the left edge is “ mgh ”, and she/he also easily understand that the potential energy of the ball at the right edge is “ mgh ” because it is at the same height. However, if the ball jumps out of the bowl at the right edge, it must have the kinetic energy “ $(1/2)mv^2$ ”. As a result, a strange equation “ $mgh = mgh + (1/2)mv^2$ ” is derived where the energy of the ball is not conserved. The learner can then understand that his/her prediction is wrong by the equation more easily than by the behavior simulation.

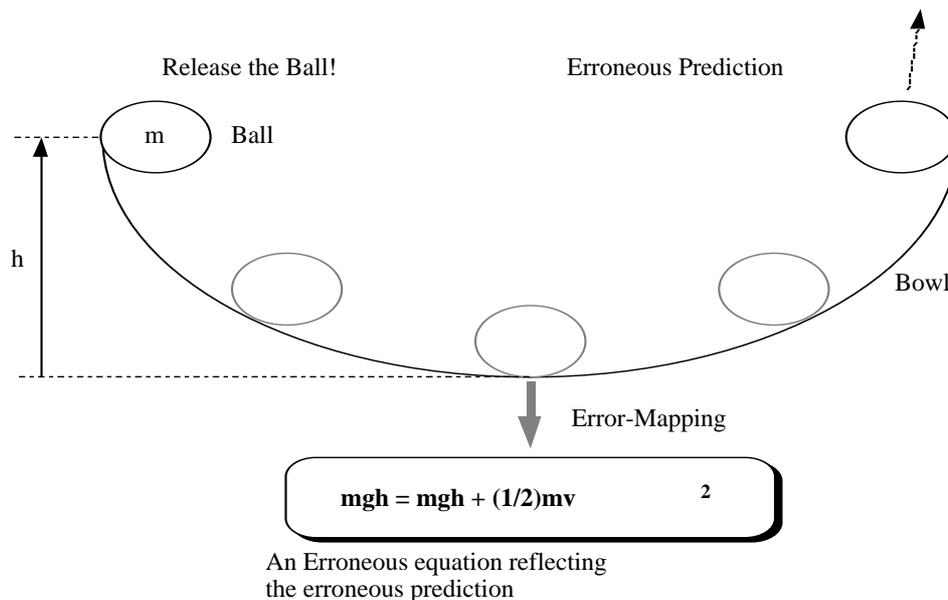


Figure 14. An erroneous prediction of behavior and the erroneous equation reflecting the prediction.

3. *To categorize qualitative difference and its effect:* The effect of EBS depends on how strange it behaves. In order to make use of EBS adequately, it is important to manage EBS, that is, to diagnose the behavior and to estimate its effectiveness. Since the EBS-manager often finds several types of qualitative differences by using qualitative reasoning, it needs some kind of empirical rules to judge which qualitative difference is the most effective for a learner to recognize the error. The EBS-manager uses a priority of qualitative difference in velocity over acceleration. It is a simple, but mostly supportable, empirical rule. It should be, however, verified. For this purpose, the human ability to recognize qualitative difference should be investigated.

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