Abstract: A framework for assisting a learner’s progressive knowledge acquisition in simulation-based learning environments (SLEs) is proposed. In SLE, usually a learner is first given a simple situation to acquire basic knowledge, then given more complicated situation to refine it. Such change of situation often causes the change of the model to be used. Our GMW (graph of microworlds) framework efficiently assists a learner in such ‘progressive’ knowledge acquisition by adaptively giving her/him microworlds. A node of GMW has the description of a microworld which includes the model, its modeling assumptions (which can explain why the model is valid in the situation) and the tasks through which one can understand the model. The GMW, therefore, can adaptively provide a learner with the microworld and the relevant tasks to understanding it. An edge has the description of the difference/change between microworlds. The GMW, therefore, can provide the relevant tasks which encourage a learner to transfer to the next microworld and can explain how/why the behavioral change of the model is caused by the change of the situation in model-based way. This capability of GMW greatly helps a learner progressively refine, that is, reconstruct her/his knowledge in a concrete context.

1. Introduction
Simulation-based learning environments (SLEs) have a great potential for facilitating exploratory learning: a learner could act on various objects in the environment and acquire knowledge in a concrete manner. However, it is difficult for most learners to be engaged in such learning activities by themselves. The assistance is necessary at least by providing the relevant task and settings through which a learner encounters new facts and apply them. The task, in addition, should be always challenging and accomplishable for a learner. With this view, a popular way is to provide a series of increasingly complex tasks through the progression of learning. Typically, in SLEs, a learner is first provided with a simple example and some exercises similar to it to learn some specialized knowledge, then provided with more complex exercises to refine the knowledge. This ‘genetic’ [11] approach has been generally used in SLEs for designing instruction [13][16][17].

The exercises to learn the specialized knowledge in SLEs means the situations in which a learner has to consider only a few conditions about the phenomena. The exercises to refine the knowledge means the situations in which she/he has to consider many conditions. In other words, the models are different which are necessary to think about the phenomena in SLEs. Therefore, it is reasonable to segment the domain knowledge into multiple models of different complexity, which is the basic idea of ‘ICM (increasingly complex microworlds)’ approach [3][7]. In ICM, a learner is introduced to a series of increasingly complex microworlds step by step, each of which has the simplified/focused domain model to its degree. This makes it easier to prevent a learner from encountering too difficult situations during exploration and to isolate the error about a segment of knowledge from the others, which greatly helps debug a learner’s misunderstandings. Several systems have been developed according to ICM approach and their usefulness has been verified [7][18][19][20][21].

The limitations of these systems are that they have little adaptability, and that they can hardly explain the differences between the models. It is important to adaptively change the situation to each learner’s knowledge state, her/his preference, the learning context etc. It is also important to explain why the new or more refined knowledge is necessary in the new situation. Though the existing ICM-based systems are carefully designed for progressive knowledge acquisition, the target knowledge of each microworld and the tasks for acquiring it isn’t necessarily explicitly represented on the system (The target knowledge of a microworld means its model. We say ‘a learner has understood the model’ in the same meaning as ‘she/he has acquired the target knowledge’). This makes it difficult to customize the series of microworlds for each learner, and to explain the necessity of microworld-transitions. In order to address these problems, the followings have to be explicitly represented: (1) the target knowledge of each microworld and the tasks for acquiring it, and (2) the difference of the target knowledge between the microworlds and the tasks for understanding it.

In this paper, we propose a framework for describing such target knowledge and tasks of a series of microworlds to assist progressive knowledge acquisition. It is called ‘graph of microworlds (GMW)’: the graph structure the nodes of which stand for the knowledge about microworlds and the edges of which stand for the knowledge of the relation between them.

By using the item (1), the GMW-based system can identify the microworlds for a learner to work on next, and provide the relevant tasks for her/him to acquire the target knowledge in each microworld. By using the item (2) (especially because it is described in model-based way), the system can provide the relevant tasks for encouraging a learner to transfer to the next microworld, and explain the necessity of the transition in model-based way. For example, the task is provided in which the previous model isn’t applicable but the new or more refined model is necessary. If a learner made a wrong solution by using the previous model, the system explains why her/his solution is wrong by relating it to the difference between the previous and new models, that is, the difference of models in two microworlds. This capability of the system would greatly help a learner progressively reconstruct her/his knowledge in a concrete context.

In fact, there have been developed several SLEs which have multiple domain models. Such systems embody the ICM principle to some extent whether they refer to it or not. In QUEST [21], ThinkerTools [18][19][20]...
and DiBi [14], for example, a series of microworlds are designed to provide a learner with increasingly complex situations and tasks which help her/him acquire the domain knowledge progressively (e.g., from qualitative to quantitative behavior, from voltage value to its change, from uniform (frictionless) to decelerated (with friction) motion). In ‘intermediate model’ [9][10] and WHY [5][15], on the other hand, a set of models are designed from multiple viewpoints to explain the knowledge of a model by the one of another model which is easier to understand (e.g., to explain the macroscopic model’s behavior as the emergence from its microscopic model’s one).

These systems, however, have the limitations described above. They usually have only a fixedly ordered series of microworlds. If one would use them adaptively, human instructors are necessary who can determine which microworld a learner should learn next and when she/he should transfer to it. Even though it is possible to describe a set of rules for adaptively choosing the microworlds, the rules which aren’t based on the differences of models couldn’t explain the ‘intrinsic’ necessity of transition. This is also the case about the recent non-ICM-based SLEs with sophisticatedly designed instruction [13][16][17]. Their frame-based way of organizing the domain and instructional knowledge often makes the change of tasks or situations in instruction ‘extrinsic.’

The GMW framework addresses these problems by explicitly representing the knowledge about the microworlds and the difference between them in terms of their models, situations, viewpoints, applicable knowledge and the tasks for acquiring it.

2. GMW: The Graph of Microworlds

2.1 Specification for the Description of Microworlds

In microworlds, a learner is required not only (t1) to predict the behavior of the physical system in a situation, but also (t2) to predict the change of behavior of the system given the change of the situation. That is, there are two types of tasks each of which requires (t1) and (t2) respectively. The latter is essential for a learner to refine her/his knowledge because the change of the situation might change the model itself to be used for prediction. A learner should get able not only to accomplish the task by using a model, but also to do so by choosing the relevant model to the given situation. Our research goal is, therefore, (1) to propose a framework for describing a set of models and the differences/changes between them and, based on this description, (2) to design the functions which adaptively provide a learner with microworlds (i.e., situations and tasks) and explain how/why the models change according to the changes of situations.

The model of a physical system changes when the situation goes out of the range within which it is valid. The range can be described as the modeling assumptions, which are the assumptions necessary for the model to be valid. In this research, we consider the followings*1:

(a1) the physical objects and processes considered in a model
(a2) the physical situation of the system (e.g., a constraint on the parameters’ domains/values, the structural conditions of the system)
(a3) the behavioral range of the system to be considered (e.g., the interval between boundary conditions, the mode of operation)
(a4) the viewpoint for modeling the system (e.g., qualitative/quantitative, static/dynamic)

The change of modeling assumptions causes the model of physical system to change. From the educational viewpoint, it is important to causally understand a behavioral change of physical system related to its corresponding change of modeling assumptions. Therefore, our framework should include not only the description of (the change of) models but also the description of (the change of) modeling assumptions. In addition, it should also include the description of the tasks which trigger the change of models, that is, encourage a learner to think about the differences of models.

Based on the discussion above, we propose the framework for describing and organizing microworlds in section 2.2.

2.2 Description and Organization of Microworlds

2.2.1 Description of a Microworld

The following information is described in each microworld.

(m1) the target physical system and a model of it.
(m2) the physical objects and processes to be considered in the model (a1)
(m3) the physical situation of the system (a2)
(m4) the behavioral range of the system (a3) and the viewpoint for the modeling (a4)
(m5) the skills necessary for the model-based inference
(m6) the tasks and the knowledge necessary for accomplishing them.

The items (m2), (m3) and (m4) stand for the valid combination of modeling assumptions which corresponds to a (valid) model of the physical system (m1). The item (m5) stands for the skills used with the model for accomplishing tasks (e.g., numerical calculation for a quantitative model). The item (m6) stands for the tasks to be provided for a learner, to each of which the knowledge necessary for accomplishing it (the subset of

*1 We reclassified the modeling assumptions discussed in [6].
(m1)-(m5)) is attached.

From the viewpoint of model-based inference, there are two types of tasks: the task which can be accomplished by using the model of the microworld it belongs to, and the task which needs the transition to another microworld (that is, which needs another model) to be accomplished. All of the task (t1) are the former type. The tasks (t2) which don’t need the change of the model (i.e., the given change of conditions doesn’t cause the change of modeling assumptions) are also the former type. They are called ‘intra-mw-tasks.’ The knowledge necessary for accomplishing an intra-mw-task can be described by using (m1)-(m5) of the microworld it belongs to. The tasks (t2) which need the change of the model (i.e., the given change of conditions causes the change of modeling assumptions) are the latter type. They are called ‘inter-mw-tasks.’ The knowledge necessary for accomplishing an inter-mw-task is described by using (m1)-(m5) of the microworld it belongs to and (m1)-(m5) of the microworld to be transferred to. The description of inter-mw-task includes the pointer to the microworld to be transferred to.

2.2.2 Organization of Microworlds

In order to organize the set of microworlds as described above, we propose the ‘Graph of Microworlds (GMW).’ The GMW makes it possible to adaptively generate the series of microworlds to each learner. It is the extension of the ‘Graph of Models (GoM)’ [1][2] which is the framework for describing how the model of a physical system can change by the change of its constraints. The nodes of GoM stand for the possible models of the system and its edges stand for the changes of modeling assumptions (which are called ‘model-transitions’). The GoM is applied to model identification by observational data, fault diagnosis etc.

We extend the GoM to be the GMW the nodes of which stand for the microworlds and the edges of which stand for the possible transitions between them. Two educational concepts are introduced into GMW: the knowledge which a learner could acquire by understanding the model of a microworld, and the task by accomplishing which she/he could understand the model. The target knowledge of a microworld is its model, modeling assumptions and the skills used with the model (i.e., (m1)-(m5)). In order to encourage a learner to acquire it, the system provides her/him with the intra-mw-tasks of the microworld.

In order to encourage a learner to transfer to another microworld, on the other hand, the system provides her/him with the inter-mw-tasks. The GoM provides her/him with the inter-mw-task, the target knowledge of which is the difference between the knowledge about the two models. In GMW, two nodes have the edge between them if the difference between their target knowledge is sufficiently small (i.e., the transition between two microworlds is possible if it is educationally meaningful as the evolution of models). In the neighborhood of a microworld, therefore, there are a few microworlds which are similar to it in terms of the target knowledge. This makes it possible for the system to adaptively choose the next microworld according to the learning context.

(Example-1) Curling-like Problem (1)

Figure 1a shows a ‘curling-like’ situation. At the position $x_o$, a stone $M_1$ is thrown by a player with the initial velocity $v_o$, then slides on the ice rightward until it collides with another stone $M_2$ at the position $x_1$. If the friction on the ice isn’t negligible and the initial velocity is small, it may stop between $x_0$ and $x_1$ (described as ‘the interval $[x_0, x_1]$’ without collision. By the player’s decision, the interval before/after the collision, the instant of collision) and viewpoints (e.g., qualitative/quantitative).

When modeling the behavior of this physical system, there can be various physical situations (e.g., the initial velocity is small/large, the friction is/isn’t negligible, the ice is/isn’t swept), behavioral ranges (e.g., the interval before/after the collision, the instant of collision) and viewpoints (e.g., qualitative/quantitative). Therefore, several models are constructed corresponding to them. These models are, with the tasks for understanding them, then organized into the GMW (as shown in Figure 1b).

Some of the modeling assumptions and tasks in the microworlds are described as follows:

MW-1: (m1) $v(t) = v_0, x(t) = x_0 + v_0 t$

(m2) uniform motion (no force works on $M_1$)

(m3) $0 < v_0 < v_1$, $\mu < \epsilon$, not sweep [$x_o, x_1$])

(m4) position($M_1$) is in [$x_o, x_1$]

(m5) numerical calculation

MW-2: (m1) $a(t) = -\mu_2 M_2 g, v(t) = v_0, M_1 g t, x(t) = x_0 + v_0 t - \mu_2 M_2 g t^2/2$

(m2) uniformly accelerated motion, frictional force from the ice

(m3) $0 < v_0 < v_1$, $\mu_1 > \epsilon$, not sweep [$x_o, x_1$])

(m4) position($M_1$) is in [$x_o, x_1$]

(m5) numerical calculation

MW-3: (m1) $a(t) = -\mu_2 M_2 g, v(t) = v_0, M_1 g t, x(t) = x_0 + v_0 t - \mu_2 M_2 g t^2/2$

(m2) uniformly accelerated motion, frictional force from the ice, heat generation by sweeping, melt of the surface of the ice by the heat (which makes the coefficient of friction decrease to $\mu_2$, and the temperature of the surface of ice increase to zero centigrade degree)
Figure 1a. ‘Curling-like’ Situation

Figure 1b. Graph of Microworlds

Suppose a learner who has learned ‘uniform motion’ by the intra-mw-task (1) in MW-1 is provided with the inter-mw-task (2*) of MW-1. She/he would be encouraged to transfer to MW-2 because the friction becomes not negligible by the change of physical situation in the task (by accomplishing this task, she/he would learn the ‘decelerated motion’ and ‘frictional force,’ which is the difference between MW-1 and MW-2). Suppose, on the other hand, she/he is provided with the inter-mw-task (3*) of MW-1. She/he would be encouraged to transfer to MW-4 because, in order to accomplish the task, it is necessary to consider the behavioral range (after collision) which is out of consideration in MW-1 (she/he would learn the ‘elastic collision,’ which is the difference between MW-1 and MW-4). In addition, suppose a learner is provided with the inter-mw-task (2*) in MW-4. She/he would be encouraged to learn the ‘heat generation’ and ‘melt of the ice,’ that is, to transfer to MW-5. In the similar way, the inter-mw-task (2*) in MW-4 encourages a learner to learn the ‘inelastic collision,’ that is, to transfer to MW-5.

3. Assistance in Microworld-Transition by Parameter Change Rules

There are two types of microworld-transitions: the one which changes the behavioral range of the system to be considered or the viewpoint for the modeling (m4), and the other which (slightly) changes the physical situation of the system (m3). In the former, a learner usually can’t execute the procedure she/he previously learned for getting a solution because the different type of knowledge/skills (model) is required in the new microworld (suppose the transition from MW-1 to MW-4 in Figure 1b, for example). This would sufficiently motivate her/him to transfer to the new microworld. In the latter, on the other hand, a learner often could execute the previous procedure as it is. She/he, therefore, might get a wrong solution because the previous knowledge/skill (model) by itself is irrelevant to the new microworld (suppose the transition from MW-1 to MW-2 in Figure 1b, for example), and she/he might not be aware of the error. This makes it difficult for her/him to transfer to the new microworld.

In such a case, it is necessary to explain why the learner’s solution is wrong compared with the correct solution, in other words, how/why her/his previous model irrelevant to the new situation differs from the
PC-Rule-2: If sliding(M_1, ice), and MW-1 to MW-2 because it asks the (change of) velocity of M1 when the coefficient of friction
By using PC-Rule-1, it is inferred that the inter-mw-task (m6)-(2*) of MW-1 is relevant to the transition from
(a change of) the (change of) friction of M1 because the coefficient of friction of M1 increases.

If the modeling assumptions (m2) change to (m2*), and the modeling assumptions (m3) change to (m3*)
(and the other modeling assumptions (m4) don’t change)

Then the values of some parameters qualitatively change (increase/steady/decrease)

This rule means that if the model of the physical system (i.e., the physical objects and processes to be considered) changes by the change of physical situation, the values of some parameters of the system increase/steady/decrease. Consider the assistance in transferring from one microworld to the other. First, the parameter change rule which matches them is searched. By using it, the inter-mw-task is identified/generated which asks the (change of) values of those parameters when the physical situation changes. If a learner has difficulty in the task, the explanation is generated which relates the difference between the values calculated by the two models with the difference between their modeling assumptions (i.e., the physical objects and processes to be considered). Thus, the necessity of microworld-transitions can be explained based on the difference between the phenomena she/he wrongly predicted and the ones she/he experienced in the microworld.

(Example-2) Curling-like Problem (2)
We illustrate the two parameter change rules of the GMW in Figure 1b: one is for the transition from MW-1 to MW-2 and the other is for the transition from MW-2 to MW-3. They are described as follows:

PC-Rule-1: If sliding(M_1, ice), friction(M_1, ice) = \mu_1, 0 < v_0 < v_0', not sweep([x_0, x_1]), and
changed(\mu_1 < \epsilon_1 \Rightarrow \mu_1 > \epsilon_1), and
changed(consider(uniform motion) \Rightarrow consider(uniformly decelerated motion)), and
considered(frictional force)

Then decrease(velocity(M_1, x))

PC-Rule-2: If sliding(M_1, ice), and changed(not sweep([x_0, x_1]) \Rightarrow sweep([x_0, x_1])), and
considered(heat generation, melt of the ice)

Then change(friction(M_1, ice) = \mu_1 \Rightarrow friction(M_1, ice) = \mu_2; \epsilon_1 < \mu_2 < \mu_1),
increase(velocity(M_1, x), position(M_1, v_1 = 0))

By using PC-Rule-1, it is inferred that the inter-mw-task (m6)-(2*) of MW-1 is relevant to the transition from MW-1 to MW-2 because it asks the (change of) velocity of M1, when the coefficient of friction \mu_1 increases. By using PC-Rule-2, on the other hand, it is inferred that the inter-mw-task (m6)-(3*) of MW-2 is relevant to the transition from MW-2 to MW-3 because it asks the (change of) position at which M1 stops when the surface the ice is swept. If a learner has difficulty in these tasks, the model-based explanations are generated by using the information in these rules and microworlds.

4. Assistance in Microworld-Transition by Qualitative Difference Rules
The assistance by parameter change rules is based on the quantitative difference of the behavior of physical systems. That is, what motivates a learner to change the model she/he constructed is the fact that the values of parameters calculated by her/his model differs from the ones observed in the microworld (which is calculated by the ‘right’ model). A learner, however, generally tends to maintain her/his current model (hypothesis). Even when the prediction by her/his model contradicts the observation, she/he often tries to dissolve the contradiction by slightly modifying the model (instead of changing the modeling assumptions) [4]. In addition, quantitative differences sometimes provide insufficient information for the change of modeling assumptions. It would be, therefore, often more effective to use the qualitative/intuitive difference for explaining the necessity of microworld-transitions. In this chapter, we show the method for generating such explanation by using a set of ‘qualitative difference rules’ (which are used complementarily to parameter-change rules).

Each of qualitative difference rules describes how a model-transition effects on the qualitative states of behavior of physical systems calculated by the models (e.g., in Figure 1, the existence of the water (the melted ice made by the frictional heat) in MW-3 qualitatively much differs from the absence of it in MW-2, which is out of the scope of parameter-change rules). They are described in the following form:

If the modeling assumptions (m2) change to (m2*), and the modeling assumptions (m3) change to (m3*)
(and the other modeling assumptions (m4) don’t change)
In order to describe these rules, we first classify the differences of the states/behavior between two physical systems from some qualitative viewpoints. We then relate such differences to the ones of modeling assumptions by which they could be caused. In order to derive a set of qualitative difference rules systematically, we execute this procedure based on the qualitative process model [Forbus 84]. The procedure is described in the following two sections.

4.1 Concepts of Difference [12]

The purpose of classifying the behavioral ‘differences’ of physical systems is to provide a guideline for describing the ‘educationally useful’ qualitative difference rules, which enable the assistance to motivate a learner as much as possible. When a learner can’t explain an observed phenomenon by her/his model, she/he is motivated to modify/change it. The strength of motivation and the relevancy of modification/change would much depend on what kind of difference she/he saw between the observation and her/his prediction. In Figure 1, for example, when a learner sees the water in MW-3, she/he who still uses the model of MW-2 would be surprised because it can’t exist by her/his prediction. In addition, the deformation of stones in MW-5 (by the inelastic collision) would surprise a learner who still uses the model of MW-4 because they never deform by her/his prediction. Such differences would motivate a learner much more than the (slight) difference of the velocity of M1 or the (slight) difference of the energy of stones which might be neglected by her/his prediction. Though all of them suggest her/his error more or less, it would be better to choose the ‘most effective difference’ to be pointed out to her/him*. Therefore, the possible ‘differences’ and their ‘effectiveness’ in the behavior of physical systems should be systematically identified and classified. This, in addition, needs to be done in the model-based way because the qualitative difference rules will be described based on this identification/classification.

With this view, we use the qualitative process model [8] because of its reasonable granularity and generality. That is, we regard a physical system and its behavior as a set of physical objects which interact each other through physical processes. The objects are directly/indirectly influenced by the processes and are constrained/changed/generated/consumed. The processes are activated/inactivated when their conditions become true/false. In order to observe the objects in such a system, we introduce the following viewpoints, each of which focuses on:

- (v1) how an object exists,
- (v2) how a relation between objects is,
- (v3) how an object changes through time, and
- (v4) how a relation between objects changes through time.

If these are different between in the prediction and in the observation, a learner is supposed to recognize the difference of the behavior.

Based on the viewpoints above, the differences are identified/classified as shown in Figure 2 (they are called ‘concepts of difference’). We illustrate some of them (see [12] for more detail):

(d1) the difference about the existence of an object:
If an object exists (or doesn’t exist) in the observation which doesn’t exist (or exists) in the prediction, it is the difference.

In Figure 1, suppose the behavior of the model in MW-2 is the prediction and the one in MW-3 is the observation, the existence of water (the melted ice by the frictional heat) in the latter is recognized as the difference because it can’t exist in the former.

(d2) the difference about the attribute(s) an object has (the object class):
If an object has (or doesn’t have) the attribute(s) in the observation which the corresponding object doesn’t have (or has) in the prediction, it is the difference. In other words, the corresponding objects in the observation and prediction belong to the different object classes.

In Figure 1, suppose the behavior of the model in MW-2 is the prediction and the one in MW-3 is the observation, the ice in the former belongs to ‘(purely) mechanical object class’ because it doesn’t have the attribute ‘specific heat,’ while the one in the latter belongs to ‘mechanical and thermotic object class’ because it has the attribute ‘specific heat.’ Therefore, the ice increasing its temperature or melting in the observation is the difference. In addition, suppose the model in MW-4 is the prediction and the one in MW-5 is the observation, the stones in the former belong to ‘rigid object class (the deformation after collision can be

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* The ‘most effective difference’ here means it is the most motive one. Of course, the difference should be also ‘suggestive’ which means it suggests the way to modify/change a learner’s model. This issue is discussed in section 4.2. At present, we are giving priority to motivation in choosing the ‘most effective difference,’ which could be complemented by other ‘more suggestive (but less motive) differences.’
While the ones in the latter belong to ‘elastic object class (the deformation after collision can’t be ignored),’ the deformed stones in the observation are the differences. In both cases, the objects in the observation show ‘impossible’ natures to a learner.

In general, it would be reasonable to assume the effectiveness of these differences descends from (d1) to (d18) because of their concreteness/abstractness and simpleness/complicatedness. It is of course necessary to identify which differences of them are educationally important and how their effectiveness are ordered depending on each learning domain. The concepts of difference, however, at least provide a useful guideline for describing such knowledge.

4.2 Describing Qualitative Difference Rules

Since the concepts of differences above are identified/classified in model-based way, they can be easily related to the differences of modeling assumptions of the models. That is, each of them can suggest what kind of physical processes, which influence the objects and the constraints on them, are/aren’t considered in the models and by what kind of physical situations these processes are/aren’t to be considered. This information could be formulated into qualitative difference rules.

The qualitative difference rules are described based on the set of guidelines which are systematically derived from the concepts of differences. We illustrate an example (see [12] for more detail):

(p1) **Rules for the differences of the processes which influence (or are influenced by) an object’s (dis)appearance:**

If an object exists (or doesn’t exist) in the observation which doesn’t exist (or exists) in the prediction (d1), the followings can be the causes or effects:

1. The process which generates the object is working (or not working) in the former, and is not working (or working) in the latter.
2. The process which consumes the object is not working (or working) in the former, and is working (or not working) in the latter.
3. The influence of the process which generates the object is stronger (or weaker) than the one which consumes the object in the former, and is weaker (or stronger) in the latter.
4. By the existence (or absence) of the object, some process is working (or not working).

Therefore, the following guideline is reasonable:

(Guideline-1)

As for the change of a physical process in (m2) (and the accompanying physical situation in (m3)), the difference about the existence an object can be its effect which is generated/consumed by the process, or can be its cause the existence/absence of which influences the activity of the process.

The qualitative difference rules are used for both identifying/generating inter-mw-tasks and generating model-based explanations, as are the parameter change rules. Especially, when a learner doesn’t understand the necessity of microworld-transition, it becomes possible by using them to indicate the qualitative differences of objects which are too surprising to neglect. Since there are usually several qualitative difference rules which match the microworld-transition under consideration, there will be listed several qualitative differences. The effectiveness of them can be estimated based on the concepts of differences and the most effective differences will be chosen.

(Example-3) Curling-like Problem (3)

We illustrate the two qualitative difference rules of the GMW in Figure 1b: one is for the transition from MW-2 to MW-3 and the other is for the transition from MW-4 to MW-5. They are described as follows:

QD-Rule-1: If \( \text{sliding}(M, \text{ice}), \) and

\[ \text{changed}(\text{not sweep}([x_0, x_1]) \Rightarrow \text{sweep}([x_0, x_1])), \] and
By using QD-Rule-1, it is inferred that the inter-mw-tasks are relevant to the transition from MW-2 to MW-3 which focus on the water on the surface of the ice or the increasing temperature of the ice, that is, the differences about the existence of an object or the one about the object class. By using QD-Rule-2, on the other hand, it is inferred that the inter-mw-tasks are relevant to the transition from MW-4 to MW-5 which focus on the deformation of the stones after collision, that is, the differences about the object class. If a learner has difficulty in these tasks, the explanation is generated which relates these differences to the melt process, the heat generation process or inelastic collision process. These rules are, from the viewpoint of motivation, preferred to the parameter change rules matched to these microworld-transitions (the latter identify the tasks which ask the quantitative differences of parameters).

Since there is no qualitative difference rule that match the transition from MW-1 to MW-2, the PC-Rule-1 (which matches it) is used and the inter-mw-task (m6)-(2*) of MW-1 (which asks the quantitative change of the velocity of M1) is identified as the relevant task.

Concluding Remarks
In this paper, we proposed the GMW framework for assisting a learner’s progressive knowledge acquisition in SLEs. Because of its explicit description of microworlds and their differences, the GMW can adaptively navigate a learner in the domain models and generate model-based explanations to assist them. Though the implementation is now ongoing, we believe the GMW greatly helps a learner progressively reconstruct her/his knowledge in a concrete context.

References