# Intelligent Support for Authoring 'Graph of Microworlds' based on Compositional Modeling Technique

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**Abstract**

In simulation-based learning environments (SLEs), in order to make students understand the domain theory systematically, it is important to sequence a set of microworlds of various complexity (from relatively simple systems/phenomena to more complicated ones) adaptively to the context of learning. We previously proposed *Graph of Microworlds (GMW)* which is a framework for indexing a set of microworlds based on their models. By using GMW, it is possible to design a function for adaptively selecting the microworld a student should learn next, and for assisting him in transferring between microworlds. However, it isn't easy to describe GMW because, for model-based indexing, an author must have the expertise of model generation in the domain. In this paper, therefore, we propose a method for semi-automating the description of GMW by introducing a mechanism of model generation based on the compositional modeling technique. This method makes it possible to assist the author in generating a set of indexed microworlds and also assist him in considering educational meanings of the relations between microworlds. We present how to design such a function and also illustrate how it works in describing a simple GMW for the domain of mechanics.

## Introduction

In science education, it has been proved that simulation-based learning environments (SLEs), in which students can experience various phenomena in the domain (e.g., physics) by computer simulations, are very useful (Towne, 1995; Towne et al., 1993; Wenger, 1987). In SLEs, the range of (physical) systems and their behaviors is usually limited from some educational viewpoint in order for students to be able to understand the laws/principles behind the observed phenomena. This is called a *microworld*. In order to make students understand the whole theory of the domain systematically, therefore, it is necessary to sequence a set of microworlds of various complexity (from relatively simple systems/phenomena to more complicated ones) adaptively to the context of learning.

In designing such a function, it is essential to appropriately index a set of microworlds. Most of the current SLEs and authoring systems for them, by indexing a set of microworlds with the *labels* which represent their educational objectives and/or difficulty, provide the framework for sequencing them according to various teaching strategies (Merrill, 1999; Murray et al., 2003, for example). However, in order to facilitate a conceptual understanding of the domain, it is important to explain why, in the situation given by a microworld, the laws/principles are applicable and why the model is valid. It is also important to explain why/how the model changes if the situation is changed. In order to make such explanations, it is necessary to index a set of microworlds based on their *models* not mere labels.

Therefore, for adaptive sequencing of a set of microworlds in SLEs which aim at a conceptual understanding of the domain, we proposed a *Graph of Microworlds (GMW)*, which is a framework for indexing the microworlds and the relations between them based on their models (Horiguchi and Hirashima, 2005). We also indicated that, by using the ability in model-based inference of this framework, it becomes possible to design a function for adaptively selecting the microworld to which a student should transfer next (i.e., which he should learn next), and a function for assisting a student in transferring between microworlds.

Though GMW provides sufficient indices for designing the above functions, it isn't easy to describe a GMW. An author should make a set of microworlds and organize them by indexing the microworlds and the relations between them based on their models, that is, he must have the expertise in model generation process in the domain. Most of the (non-programmer) authors, therefore, would have great difficulty in describing GMW.

In this paper, therefore, we propose a method for semi-automating the description of GMW by introducing a mechanism of model generation based on expertise in the domain (i.e., *compositional modeling* (Falkenhainer and Forbus, 1991; Levy et al., 1997). This method makes it possible for the author not only to organize a set of microworlds by model-based indexing, but also make a set of microworlds which compose a GMW. The functions for such assistance are designed by using the method's ability to generate the model semi-automatically which embodies the given law(s)/principle(s) in the domain, and to infer how the model changes if the situation is changed.

In this paper, we first describe the related work (section 2), and then illustrate a GMW and how it works for designing the above functions (section 3). In section 4, we discuss the difficulties in describing GMW and present the framework of our method for assisting the author with compositional modeling technique. In section 5, we present how to describe the domain knowledge in order to implement our method and illustrate how it works. In section 6, we make some concluding remarks.

## Related Work

Murray classifies the current ITS-authoring systems and the functions of ITSs built with them into *pedagogy-oriented* and *performance-oriented* (Murray et al., 2003). The former systems, focusing on the function for sequencing learning contents indexed at a relatively shallow level adaptively to the context of learning (i.e., global guidance and planning in the whole domain), pay main attention to the representation of indices and teaching strategies. The latter systems, focusing on providing rich learning environments about each learning content (i.e., authentic content and feedback on errors), pay main attention to the representation of the domain-specific phenomena and problem solving processes.

Current SLE-authoring systems and the SLEs built with them belong to the latter. That is, most of them pay main attention to making the precise model of a specific content (i.e., microworld), but have the framework for indexing learning contents only at a relatively shallow level (Merrill, 1999; Murray et al., 2003, for example).

However, especially in SLEs which aim at a conceptual understanding of the domain, it becomes necessary to index the microworlds and the relations between them at a deeper level, that is, based on their models. The importance of considering differences between models in the SLEs which have multiple microworlds has been pointed out in earlier systems. For example, Burton et al. proposed a methodology for assisting students' progressive learning with a sequence of *increasingly complex microworlds* (called *ICM*) (Burton et al., 1984), and several systems based on ICM have been developed (Fischer, 1988; Towne et al., 1993; White and Frederiksen, 1993; White and Frederiksen, 1990). In these systems, however, the sequences are fixed (i.e., the microworlds and the relations between them aren't explicitly indexed) and they can't be adaptively changed. On the other hand, Hirashima et al. proposed a framework for indexing problems in mechanics based on the models and situations they deal with in order to sequence them adaptively (Hirashima et al., 1994; Hirashima et al., 1993). However, its ability in model-based inference is limited (especially, as it doesn't cover behavioral differences between models), and the method for assisting authors in indexing problems isn't given.

The framework of GMW and the method proposed in this paper for describing GMW present a solution to the problems these current systems have.

## Assistance Provided by GMW

GMW (Horiguchi and Hirashima, 2005) consists of a set of microworlds each of which has a model which embodies some specific law(s)/principle(s) in the domain. Each microworld is indexed not only with the law(s)/principle(s) but also with the *situation* in which the model is valid. A situation is the system's structure and its state assumed in a model. It is represented by a set of *modeling assumptions*, which are the descriptions of the viewpoint in modeling the system, the behavioral range of the system to be considered and the boundary conditions of the system. Modeling assumptions represent the conditions concerned with the system's structure and its state on which the model is valid.

By indexing each microworld not only with the law(s)/principle(s) but also with the situation, the *educationally meaningful* transition between microworlds can be designed. Suppose that after learning some law(s)/principle(s) with a model of a situation, a student is ready to learn the next law(s)/principle(s). It isn't desirable for him to learn the next law(s)/principle(s) with a model which embodies it/them but the situation of which is completely different from the previous one. From an educational viewpoint, it is more desirable that he finds the necessity of the *evolution* of the previous model in the new situation, and consequently gets the new model which embodies the next the law(s)/principle(s). By describing modeling assumptions explicitly, it becomes possible to judge whether two microworlds are in such relation (called *educationally meaningful* relation).

*[Example-1]* An example of GMW for a physical system is shown in Figure 1. It consists of 5 microworlds, each of which is indexed with the following items:

(m1) the physical system and a model of it

(m2) the physical structure of the system: the physical objects and their relations, their attributes, and the physical processes to be considered in the model

(m3) the behavioral range of the system to be considered

(m4) the boundary conditions of the system

(m5) the skills necessary for the model-based problem solving (e.g., how to solve differential equations)

(m6) the tasks to be performed for understanding the model

MW-1 deals with a piece of domain theory *linear uniform motion* as its learning item, and has a model which embodies it. MW-2 deals with *linear accelerated motion* and *frictional force* as its learning items, and has a model which embodies them. As for MW-3, *heat generation* and *melt of the ice* are added to those of MW-2, and MW-3 has a model which embodies all of them. MW-4 and MW-5 deal with *elastic collision* and *inelastic collision* respectively, and have models which embody them respectively. In addition, *parameter-change rules* are attached to the edges between MW-1 and MW-2, between MW-2 and MW-3 and between MW-4 and MW-5, which relate the difference between the situations (i.e., modeling assumptions) of two microworlds to the difference between the behaviors of their models (only the first rule is shown in Figure 1).

For example, when a student learned the learning item in MW-1, MW-2 and MW-4 are identified as the candidates he should learn next by examining the nodes adjacent to MW-1

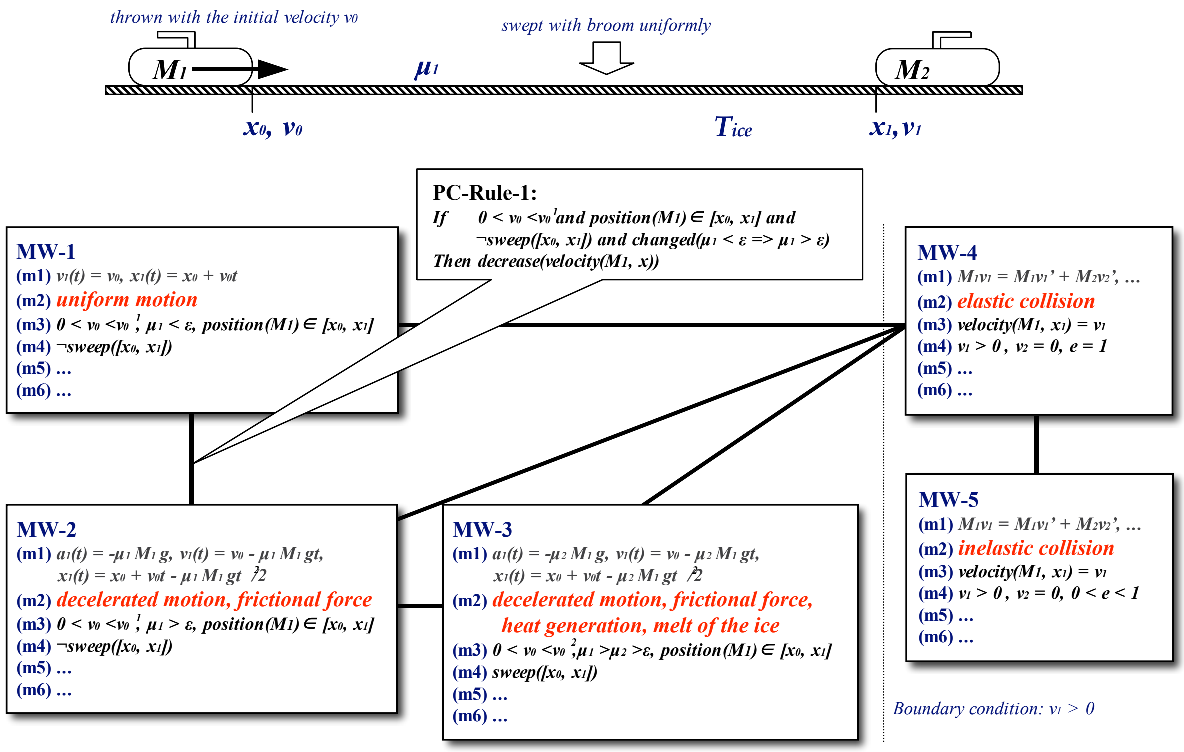


Figure 1: An example of Graph of Microworlds

in GMW. In addition, in order to assist a student in transferring from MW-1 to MW-2, it is possible to generate a task by using the parameter change rule attached to the edge between them, such as: *derive the velocity of $M_1$ when the value of* $\mu_1$ *becomes greater and the friction becomes not negligible*. It is also possible to generate the explanation of how/why the velocity of $M_1$ changes. In this task, the necessity of the model of MW-2 is strongly suggested because the difference between the velocities of $M_1$ before/after the change of $\mu_1$ can't be explained only by the model of MW-1. Such a task which needs the transition to another microworld to be performed is called *inter-mw-task*, while a task which can be performed with only the model of the microworld it belongs to is called *intra-mw-task*.

## Method for Assisting Authors in Describing GMW

### Definition of the Problem

In science education, there are a set of key concepts and laws/principles which compose the domain theory and must be learned in order for a student to understand the theory. We call them *learning items*. The learning items usually have the relations of *prerequisite*, *whole/part*, and others between them (e.g., *acceleration* should be learned before *Newton's 2nd law*, and *linear uniform motion* is the specific case of *linear accelerated motion*). In other words, they have a partial ordering. The lessons in school and the chapters in textbooks are sequenced according to the ordering. Therefore, we suppose a *learning item network* is given which consists of a partially ordered set of learning items each of which deals with some specific law(s)/principle(s) in the domain. An author is required to describe a GMW which satisfies the following requisites (see the upper part of Figure 2):

(1) The set of microworlds in the GMW has the same partial ordering as the learning item network (i.e., they are isomorphic), and each microworld has a model which embodies the law(s)/principle(s) dealt with by its corresponding learning item [1].

(2) Each microworld is indexed by the law(s)/principle(s) it deals with, the model which embodies the law(s)/principle(s) and its modeling assumptions (i.e., (m1)-(m4) in section 3.1). (The relations between two microworlds are indexed by the difference between these.)

(3) Two microworlds which correspond to two adjacent learning items in the learning item network have the *educationally meaningful* relation as much as possible.

As for these requisites, there are the following difficulties:

(1) It is, in general, difficult to find the situation (i.e., the system's structure and its state) which embodies the given law(s)/principle(s) because its search space becomes vast.

[1] A model in a microworld may include the law(s)/principle(s) dealt with by the learning item(s) which is/are upper than the microworld's corresponding learning item in the learning item network.

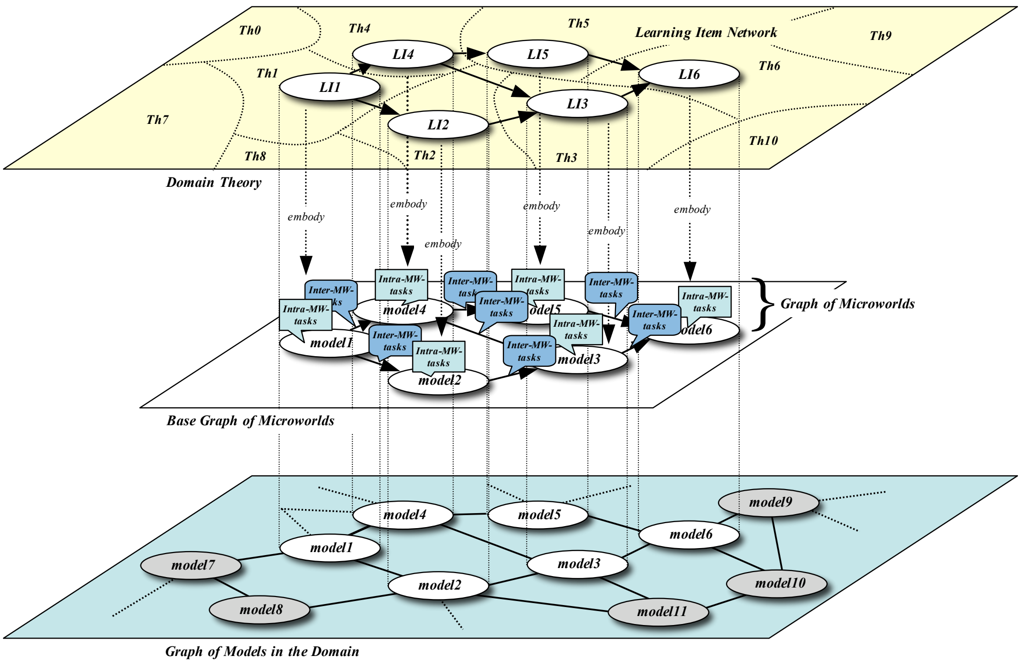


Figure 2: The structure of Graph of Microworlds

(2) It needs the expertise in model generation process in the domain to index the models in microworlds with the law(s)/principle(s) behind them and their modeling assumptions, especially because modeling assumptions are usually implicit information in models.

(3) Because of the same reason as above, it is difficult to identify the relation between two microworlds based on the differences of their models and modeling assumptions and to judge whether the transition between them is educationally meaningful. Moreover, it is also difficult to make a set of microworlds which includes the educationally meaningful relations following the partial ordering in the learning item network.

## Method for Assistance

Consider the network which consists of the *possible* models (i.e., consistent combinations of modeling assumptions) and the *possible* relations between them (i.e., consistent perturbations of modeling assumptions) in the domain. We call it *Graph of Models (GoM)* [2] [3] . We suppose that the consistency of models and relations between them can be judged based on the domain theory.

In this paper, we propose a method for assisting an author in describing GMW by a *generation-test* method, in which he semi-automatically generates the models which belong to the GoM in the domain one after another, and judges whether each of them is appropriate to the GMW from an educational viewpoint. That is, we suppose that GMW can be described by extracting a subgraph from the GoM from an educational viewpoint (called *base GMW*), and by adding intra-/inter-MW-tasks (including the tools necessary for performing them) to it (see the lower part of Figure 2). The method we propose here is for the former (i.e., describing base GMW), not for the latter. Hereafter, we call base GMW simply *GMW*.

In order to implement the above method, we need a mechanism of model generation which guarantees that the combination of modeling assumptions in a model generated by it is consistent, and that the difference of modeling assumptions in a relation between two models is consistent, based on the domain theory. That is, the target of this method is a teacher who describes GMW as the teaching material in his class, not a programmer who describes domain theory for the mechanism of model generation. We suppose that domain theory is appropriately described by a programmer according to the guide in organizing it (presented in section 5).

In our method, *compositional modeling* technique (Falkenhainer and Forbus, 1991; Levy et al., 1997) is used as such a mechanism, which generates the models in the domain based on explicit modeling assumptions. In composi-

[2] Possible models/relations mean they can theoretically exist but need to be described in order to exist concretely. Because the number of possible models/relations in the domain is vast, an author can't describe the whole GoM. However, he needn't do so because what he should describe here is a set of possible models/relations which are educationally useful and cover the given learning item network (i.e., a GMW).

[3] The GoM proposed by Addanki et al. (Addanki et al., 1991) deals with only the *general/specific* relation between models, while we extend it for dealing with other types of relations (see section 5).

```
(defModel (kinetic-friction ?obj ?flr)
        :Individuals ((?obj :conditions (m-object ?obj))
                      (?flr :conditions (m-floor ?flr)))
        :Assumptions ((CONSIDER (k-cof ?obj ?flr)))
        :Conditions ((on ?obj ?flr)
                     (gt (mag (normal-force ?obj ?flr)) 0)
                     (gt (mag (velocity-t ?obj ?flr)) 0))
        :Relations ((Quantity (k-friction ?obj) :p-vector)
                    (= (mag (k-friction ?obj))
                       (* (k-cof ?obj ?flr) (mag (normal-force ?obj ?flr))))
                    (= (dir (k-friction ?obj))
                       (rev (dir (velocity-t ?obj ?flr))))))
```

Figure 3: An example of model fragment

tional modeling, domain theory is described as a set of primitives called *model fragments* each of which stands for a specific law/principle in the domain (called a *library* of model fragments) . Each model fragment consists of two parts: One is a partial situation (i.e., a partial system's structure and its state) to which the law/principle can be applied. This is described as a set of modeling assumptions. The other is a set of constraints which becomes valid when such a partial situation does exist. When a situation (i.e., a system's structure and its state) is inputted into the mechanism, a set of model fragments each of which matches the modeling assumptions which are true in the situation are instantiated, and the set of constraints given by these model fragments are outputted as the model of the situation. (Since this technique mainly targets physical systems, our method also does so.) An example of model fragment used in our implementation is shown in Figure 3.

By introducing compositional modeling mechanism, it is automated to index the models of a given situations with their modeling assumptions. It is, however, still difficult to find the situations which embody the given laws/principles. In our method, therefore, the author describes GMW as follows:

(1) First, suppose the author can find a situation which embodies the law(s)/principle(s) dealt with by a learning item in the given learning item network. The compositional modeler automatically generates the model and indexes it by its modeling assumptions.

(2) Then, he perturbs this situation by changing some parameter(s) of the system [4] . The compositional modeler automatically generates the model of this new situation and indexes it by its modeling assumptions [5] .

(3) If the new model embodies the law(s)/principle(s) dealt with by another learning item which is adjacent to the former learning item in the learning item network, he decides whether it is added to the GMW or not. If he judges that the difference between these two models is educationally meaningful, he adds the new one and the new edge between them to the GMW.

(4) By repeating (2) and (3) to grow the GMW, the author would finally get the whole GMW which embodies all the learning items in the given learning item network by a set of microworlds (and the set of microworlds has the same partial ordering as the learning item network).

By this procedure, the difficulties indicated in section 4.1 are solved except the following two points: One is to find the initial situation and its model from which the GMW is grown. The other is to identify the relation between two models based on the perturbation of situation (i.e., the difference of modeling assumptions) and to judge whether it is educationally meaningful or not. As for the former, however, it is sufficient to find only one situation and its model which embody an arbitrary learning item in the learning item network, which would be much easier than find a set of microworlds covering all the learning items. As for the latter, the function is desirable which advises the author on what physical meaning a difference of modeling assumptions has. In order to design such a function, it is necessary to classify modeling assumptions based on their physical meanings. The classification means organizing the library of model fragments based on the modeling assumptions included in each model fragments.

In the next section, therefore, we consider what types of modeling assumptions are used in generating models of physical systems and classify the modeling assumptions. Based on this classification, we also present how to organize a library of model fragments in the domain of physics. Though previous researches have presented several ways of classifying modeling assumptions and organizing a library of model fragments, we try the reclassification of modeling assumptions especially from the viewpoint of difference of models caused by the perturbation of situation. We finally describe the design of the function for inferring the relation between two models based on the difference of their modeling assumptions.

[4] A mechanism is necessary which infers what change of parameter(s) causes what change of a situation (i.e., change of modeling assumption(s)). In this paper, we omit the description of this mechanism on account of limited space.

[5] The consistency of the model of the new situation (i.e., the new combination of modeling assumptions) is guaranteed by the compositional modeler (inconsistent ones are detected and deleted by it).

## Relations between Models based on the Difference of Modeling Assumptions

### Modeling Assumptions

We classify the modeling assumptions made in generating models of physical systems into *constraints of physical structure (CPS)* and *constraints of operating range (COR)*. In a model or model fragment, at least one of these respective assumptions must be specified.

*Constraint of physical structure (CPS)* is the assumption which specifies what kind of objects, relations and their attributes in a physical system are considered (where, the specification about objects is called *constraint of physical objects (CPO)*, and the one about relations and attributes is called *constraint of physical attributes (CPA)*). CPS represents the decisions about perspectives and granularity in modeling a physical system. For example, the specification about whether two connected metal blocks are considered as one object or two objects is a CPO. The specification about whether their mechanical relations/attributes (e.g., mass, applied forces) or their electrical ones (e.g., current, resistance) are considered is a CPA.

Physical phenomena occur assuming a physical system is in a specific state. When the state changes, the model may become invalid. Therefore, a model must have the specification about the range (in its state space) within which it is valid. It is called *constraint of operating range (COR)* (where, the one which can be specified by (a set of) physical attributes is called *constraint of physical range (CPR)*, and the one which need to be specified by (a set of) conceptual attributes (e.g., complex shape of an object, complex positional relation between objects) is called *constraint of conceptual range (CCR)*). For example, since a model of two connected blocks' motion with the internal force between them assumes their velocities are the same, such specification is necessary. A model of a resistance assuming its value is constant needs the specification that its current and voltage are within the proportional range. These are CPRs. In a model of a block b descending an inclined plane p by gravity from the gravitational field g, their positional relation must be appropriately specified (e.g., $in(b, g)$, $on(b, p)$). This is a CCR.

In each type of these modeling assumptions, there are often the sets of exclusive ones which can't be made simultaneously. For example, in a physical system which has a CPS, it isn't allowed to make assumptions *transient state* and *steady state* simultaneously as COR. In a physical system which has a CPO, it isn't allowed to make assumptions *consider friction between two blocks* and *not consider friction between them* simultaneously as CPA. Moreover, in a physical system, it isn't allowed to make assumptions *view a block as a rigid object* and *view it as an aggregation of atoms/molecules* as CPO.

### Relations between Models

When the domain theory is described as a library of model fragments, each model fragment stands for a specific physical law/principle. A set of CPS and COR is attached to each model fragment as its condition of application. The model of a situation (i.e., the system's structure and its state) is generated as a conjunction of the constraints given by the instantiated model fragments. Its modeling assumption is the conjunction of the ones attached to each model fragments (the consistency of the conjunctions is guaranteed by the compositional modeling mechanism).

By grouping the model fragments each of which has exclusive modeling assumption(s), it is possible to design the function for suggesting the relation between the models in two microworlds before and after the perturbation of situation. That is, first, the two sets of model fragments are compared, each of which composes each model. Then, if a pair of model fragments each of which belongs to each model and matches the same/similar partial situation has exclusive modeling assumption(s), the relation between the models is inferred from the type of the assumption. The procedure is as follows:

(0) Assume that it is possible for each model fragment in one model to find its corresponding model fragment in another model. Two model fragments corresponds to each other (called *a pair of model fragments*) if they are instantiated by matching the same/similar partial physical structure (i.e., physical objects and their relations/attributes) in the system (when two models have different CPOs, it is assumed that the method is given for finding the correspondence between the physical objects considered in them). If a model fragment in one model can't find its corresponding model fragment in another model, the following procedure is carried out based on its modeling assumptions themselves.

(1) When two model fragments which corresponds to each other have exclusively different CPOs, it is inferred that the difference of two models is *change of the viewpoint/granularity* about the partial system which they match.

(2) When two model fragments which corresponds to each other have the same CPOs and exclusively different CORs, it is inferred that the difference of two models is *change of the operating range* about the partial system which they match.

(3) When two model fragments which corresponds to each other have the same CPOs, the same CORs and exclusively different CPAs (i.e., it isn't possible to find the correspondence between the relations/attributes considered in them), it is inferred that the difference of two models is *general/specific* about the partial system which they match [6] .

The differences inferred by the above procedure are sometimes concerned with all the pairs of model fragments which compose the models (i.e., the whole system), or concerned with a pair of model fragments (i.e., the partial system which

[6] It is assumed that there is some kind of *inclusion* relation between the CPAs of two model fragments. For example, Levy et al. defined a *simpler-than* relation based on the *superset/subset* relation between the causal orderings of (the output quantities of) two model fragments (Levy et al., 1997).

they match). In the former case, they stand for the global differences between two models, while in the latter case, they stand for only the local differences between them. In general, because there can be multiple global/local differences in two models, it is difficult to determine *the most appropriate difference* between them.

In this research, therefore, we adopt the following method: (1) the authoring system first enumerates the possible global/local differences between two models by the above procedure, then the author, referring to them, identifies the most appropriate difference and judges its educational meaning (i.e., determines whether there is the edge between them and its type). In our method, since the new model is generated by perturbing the old one's situation (i.e., modeling assumptions), it is expected that there are at most a few differences between them and that the author has little difficulty in the identification and judgement.

*[Example-2]* Figure 4a shows the physical system in which an object $b_1$ is put on an inclined plane $p_1$ (to which a horizontal plane $p_2$ is connected). Figure 4b shows a model (i.e., a set of instantiated model fragments) of a situation of this system in which $b_1$ remains at rest on $p_1$ because the tangential component of $b_1$'s gravity on $p_1$ is smaller than the maximum static friction between $b_1$ and $p_1$. It (called model-1) consists of 5 model fragments, including *static friction* and *rest*. If the coefficient of static friction is decreased in this situation, another situation may occur in which $b_1$ moves downward accelerated by its gravity (and the kinetic friction). The model of this situation (called model-2) is shown in Figure 4c and it consists of 5 model fragments, including *kinetic friction* and *linear acc-motion*.

Because the model fragments *gravity* in model-1 and model-2 are instantiated by matching with the same physical structure in these models, they correspond to each other. As for the model fragments *normal force* and *acceleration* in both models, the matters are the same. These model fragments compose the common part of model-1 and model-2 because their CORs are also the same in both models respectively.

The model fragments *static friction* in model-1 and *kinetic friction* in model-2 correspond to each other because of the same reason. However, their CPRs which specify the range of the value of the coefficient of static friction are exclusively different. It is, therefore, inferred that there is a difference between these models in 'the change from static friction to kinetic friction because of the change in the value of the coefficient of static friction.' The model fragments *rest* in model-1 and *linear acc-motion* in model-2 also correspond to each other because of the same reason. Their CPRs which specify the range of the value of $b_1$'s acceleration are exclusively different. It is, therefore, inferred that there is a difference between these models in 'the change from rest to linear accelerated motion because of the change in the value of $b_1$'s acceleration.'

Referring to these two differences enumerated by the authoring system, the author identifies the most appropriate difference and judges its educational meaning.

*[Example-3]* In Figure 4, if the time variable of model-2 is increased, $b_1$ transfers from $p_1$ to $p_2$ (i.e., $on-floor(b_1, p_1)$ changes to $on-floor(b_1, p_2)$). The model of this new situation (called model-3) is shown in Figure 4d and it consists of 4 model fragments, including *linear uni-motion*.

The model fragments *gravity* and *acceleration* in model-2 and model-3 compose the common part of these models because of the same reason as Example-2.

The model fragments *kinetic friction*, *normal force* in model-2 and *normal force* in model-3 don't have their corresponding model fragments. The reason is that their CCRs which specify the positional relation among $b_1$, $p_1$ and $p_2$ exclusively changed because of $b_1$'s transition from $p_1$ to $p_2$. It is, therefore, inferred that there are the differences between these models in 'the disappearance of kinetic friction and normal force between $b_1$ and $p_1$, and the appearance of normal force between $b_1$ and $p_2$ because of the change in the positional relation among $b_1$, $p_1$ and $p_2$.'

The model fragments *linear acc-motion* in model-2 and *linear uni-motion* in model-3 correspond to each other because they are instantiated by matching the same physical structure in these models. Their CPRs which specify the range of the value of $b_1$'s acceleration are exclusively different. It is, therefore, inferred that there is a difference between these models in 'the change from linear accelerated motion to linear uniform motion because of the change in the value of $b_1$'s acceleration.'

## Concluding Remarks

In this paper, we proposed a method for assisting an author in describing GMW. The feature of our method is that it uses a problem solver (i.e., model generator) in the domain for indexing a set of microworlds semi-automatically. We think this is inevitable in order to assist the authors in indexing them based on their models, aiming at the ability in inference about the difference between models.

Introducing the powerful model of expertise may cause the problems of its cost and limited applicability. However, we think they can be reduced by adopting compositional modeling technique. That is, it has a framework for judging the consistency of models at a conceptual level (i.e., based on modeling assumptions), and the methods for describing domain knowledge (i.e., library of model fragments) at that level have been developed in literature. We think preparing a set of templates of model fragments in each domain would provide the guideline for describing the domain knowledge. Moreover, because this technique works in any domain of physics and provides the model generator which widely covers its domain, our method would be applicable to many domains of physics. We are planning to verify the usefulness of the prototype system which implements our method, and to discuss the method for describing the expertise in model generators.

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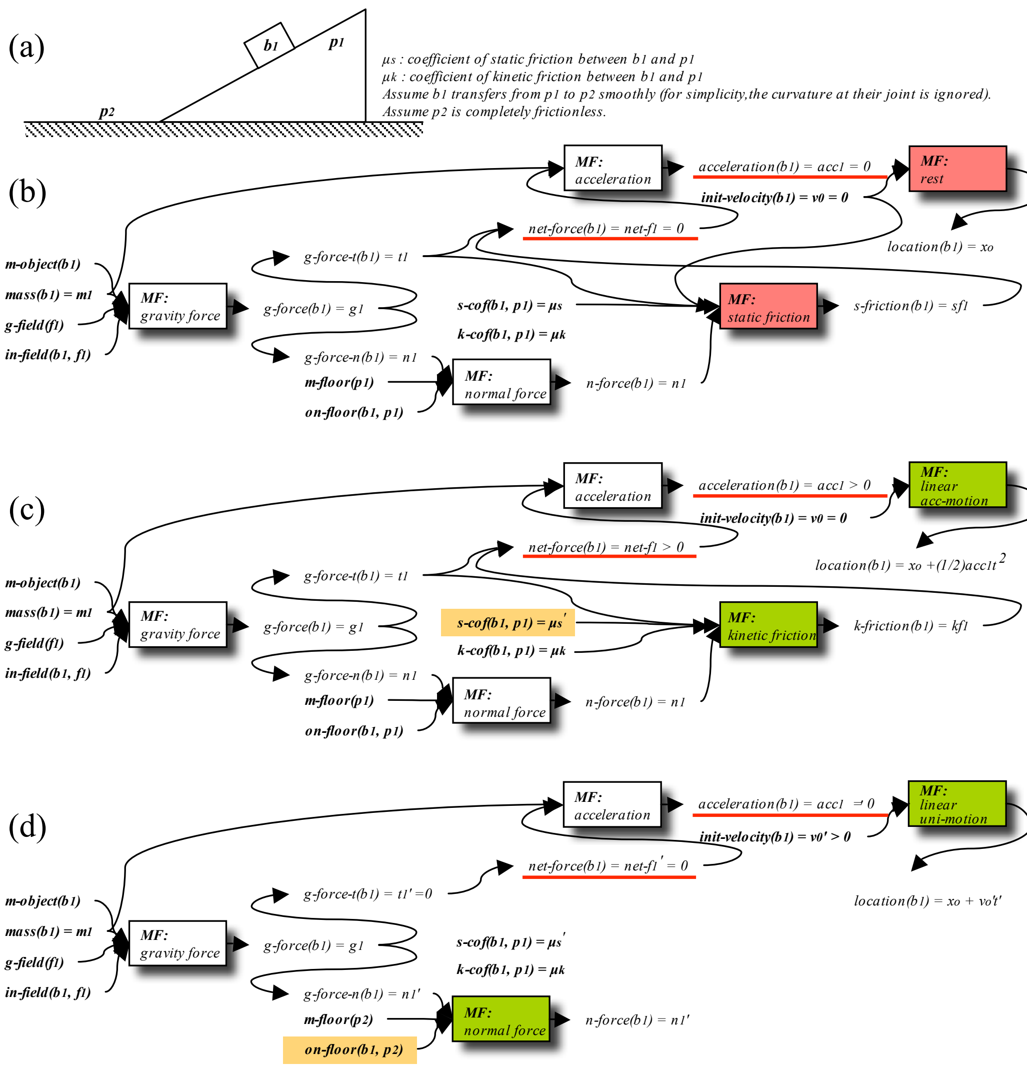


Figure 4: An example of difference between models

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