IEICE TRANS. INF. & SYST., VOL. E77-D, NO. 1 JANUARY 1994

PAPER *Special Issue on Intelligent CAI and Hypermedia*

An Indexing Framework for Adaptive Arrangement of Mechanics Problems for ITS

Tsukasa HIRASHIMA†, ***Member***, **Toshitada NIITSU**†, **Kentaro HIROSE**†, ***Nonmembers***, **Akihiro KASHIHARA**† ***and*** **Jun'ichi TOYODA**†, ***Members***

SUMMARY This paper describes an indexing framework for adaptive arrangement of mechanics problems in ITS (Intelligent Tutoring System). There have been some studies for adaptive arrangement of problems in ITS. However, they only choose a solution method in order to characterize a problem used in the practice. Because their target domains have been sufficiently formalized, this kind of characterization has sufficed to describe the relations between any two problems of such a class. In other words, here, it is enough to make students understand only the solution methods for the given class of problems. However, in other domains, it is also important to understand concepts used in the problems and not only to understand solution methods. In mechanics problems, concepts such as mechanical objects, their attributes, and phenomena composed of the objects and the attributes also need to be taught. Therefore, the difference between solution methods applied is not sufficient to describe the difference between two given problems. To use this type of problems properly in the practice, it is necessary to propose an advanced new characterization framework. In this paper, we describe a mechanics problem with three components: (1) surface structure, (2) phenomenon structure, (3) solution structure. Surface structure describes surface features of a problem with mechanical objects, their configuration, and each object's attributes given or required in the problem. Phenomenon structure is described by attributes and operational relations among them included in the phenomenon specific to the surface structure. Solution structure is described by a sequence of operational relations which compute required attributes from given attributes. We call this characterizing indexing because we use it as index of each problem. This paper also describes an application of the indexing to arrangement of problems. We propose two mechanisms of control: (a) reordering of a problem sequence, and (b) simplifying of a problem. By now, we have implemented basic functions to realize the mechanisms except for the part of interface.

key words: *ITS, adaptive arrangement of problems, indexing of problems, mechanics problem*

1. Introduction

A major objective of ITS (Intelligent Tutoring Systems) is to enhance the students' capability of solving problems [1], [2]. Students who can solve example problems cannot always solve practical problems. This fact suggests that, in addition to the acquisition of new knowledge, the acquisition of problem solving skills also play a crucial role in enhancing human problem solving capability. In order to develop such skills, most of ITS rely on problem solving practice. Our research aims at supporting a more advanced and elaborate form of practice of solving problems in ITS [3], [4].

In a practice, students are usually required to solve problems in a given ordering, since each of them is designed to prepare for the next. However, the problem sequence is not always adequate for every student. Also, a fixed ordering of problems is often not adequate for learning all possibilities which can be supported by the problems. Therefore, arranging problems according to learning context is very important to improve the practice [5]. To realize the adaptive arrangement of problems, it is indispensable to clarify the relations between any two problems used in the practice [6]. The clarification also contributes to diagnosing and to remedying the student's failures in problem solving, because the failures are often influenced by the ordering of problems.

There have been some studies for adaptive arrangement of problems in ITS, such as SIERRA [7], FITS [8], [9], and others. However, they only choose solution methods in order to characterize problems used in the practice. Because their target domains, such as column subtraction or equation problems, have been sufficiently formalized, this kind of characterization has sufficed to describe the relations between any two problems of such a class. In other words, here, it is enough to make students understand only the solution methods for the given class of problems.

However, in other domains, it is also important to understand concepts used in the problems and not only to understand solution methods [10], [11]. For example, in mathematical word problems, equation solving methods are very important, and instruction usually will not address various concepts used in the problem in detail (e.g., dishes that appear in the problem of counting them). In contrast, in mechanics problems, concepts such as mechanical objects, their attributes, and phenomena composed of the attributes and operational relations among them, also need to be taught. For example, a block in mechanics has characteristic natures, and to understand the natures of the block are

Manuscript received July 29, 1993.
Manuscript revised September 21, 1993.

† The authors are with the Institute of Scientific and Industrial Research, Osaka University, Ibaraki-shi, 567 Japan.

very important for students. Also, in the situation set up by a problem, there are some attributes and operational relations which don't contribute to solve the problem. However, the attributes and relations are useful to solve other problems included in the same situation (in this paper, a set of all attributes and relations in the situation is called phenomenon). Therefore, the difference between solution methods applied is not sufficient to describe the difference between two given problems. To use these types of problems in properly controlling the practice, it is necessary to propose an advanced new characterization framework which can classify problems from the viewpoint of characteristic concepts in the domain.

In this paper, we describe a mechanics problem with three components: (1) surface structure, (2) phenomenon structure, (3) solution structure. Surface structure describes surface features of a problem with mechanical objects, their configuration, and each object's attributes given or required in the problem. A network composed of all attributes and operational relations among them included in the phenomenon specific to the problem, is called phenomenon structure, in this paper. Solution structure is described by a sequence of operational relations which compute required attributes from given attributes. In this paper, the characterization based on these structures is called indexing because we use it for indexing each problem. By using this index, the difference between two problems can be controlled and explained not only as the difference between their respective solution methods but also as the difference between the corresponding phenomena and surface features.

This paper describes the indexing framework and its applications to the arrangement of problems. We propose two types of control mechanisms: (a) reordering of a problem sequence and (b) simplifying of a problem, based on the framework. By now, we have implemented basic functions to realize the mechanisms except for the part of the interface. Currently, our target domain is elementary classical mechanics problems in high school.

2. An Indexing Framework for Mechanics Problems

The problem solving process of mechanics problems can be divided into three phases: (1) detection of surface structure, (2) specification of phenomenon, (3) detection of solution structure. In this paper, the indexing framework of mechanics is composed of the three components: (a) surface structure, (b) phenomenon structure, (c) solution structure. We explain each of the components with examples. Currently, we can describe problems of uniformly accelerated motion which require a quantity of an attribute from some given quantities.

2.1 Surface Structure

Some studies concerning the differences in problem solving performance between experts and novices have been focused on their performance of problem categorization [11]-[13]. These studies indicate that experts view two problems as similar when the same principle could be applied to solve both of the problems, whereas novices view two problems as similar when the problems share surface features, such as objects, configuration and their attributes. This fact suggests that such surface features influence problem solving abilities of students. Therefore, to control the surface feature of each problem in a practice is important to enhance students' problem solving skill. For example, to set and to explain a pair of problems that contain the same surface feature but the different principles, or that contain the different surface feature but the same principle, are effective for improving problem solving performance of novice students [14]. Based on this consideration, we adopt the surface structure which represents a surface feature of a problem, as an essential component of the indexing framework.

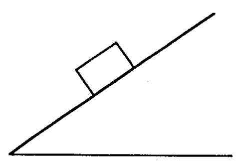
The surface structure, in this paper, consists of three elements: (1) objects set, (2) configuration pattern, (3) given or required attributes. The object set is a set of mechanical objects in a problem. The configuration pattern is a template which fixes the locative relations of each object. A problem can be identified by the surface structure composed of these three elements. Problem-1 shown in Fig. 1(a) is an example of mechanics problems. The surface structure of Problem-1 is described as Fig. 1(b). Figure 1(c) shows a diagram of Problem-1, which is specified by the objects set and the configuration pattern in the surface structure. By using the surface structure as the index, control of surface features of problems can be realized in ITS. Currently, the surface structure must be described by the author for each problem. We plan to realize automatic generator of a surface structure from sentences in a problem.

A block of mass M is put on a smooth incline quietly. The angle of the incline is ϕ and the gravity acceleration value is G. Find the velocity of the block when it moved for a distance of S on the incline?

(a) Problem-1.

objects set: [block,incline]
configuration: [block-incline]
given attributes:
[block(mass, gravitation-acceleration, moved-distance)
incline(angle)]
required attributes: [block(velocity)]

(b) Surface structure of Problem-1.



(c) Diagram of the problem of Problem-1.

Fig. 1 Surface structure.

2.2 Phenomenon Structure

When the surface structure is fixed, the phenomenon to which the problem belongs can be identified. Then, attributes which can exist in each object are fixed. These attributes which are called phenomenon attributes. Given or required attributes included in the problem are a subset of the phenomenon attributes. A solution of the problem can be regarded as a sequence of operational relations among attributes which belongs to the phenomenon. Based on this consideration, a phenomenon is described by phenomenon attributes and operational relations among them, in this paper. Figure 2 shows a part of the phenomenon structure of Problem-1. The nodes on the left side are

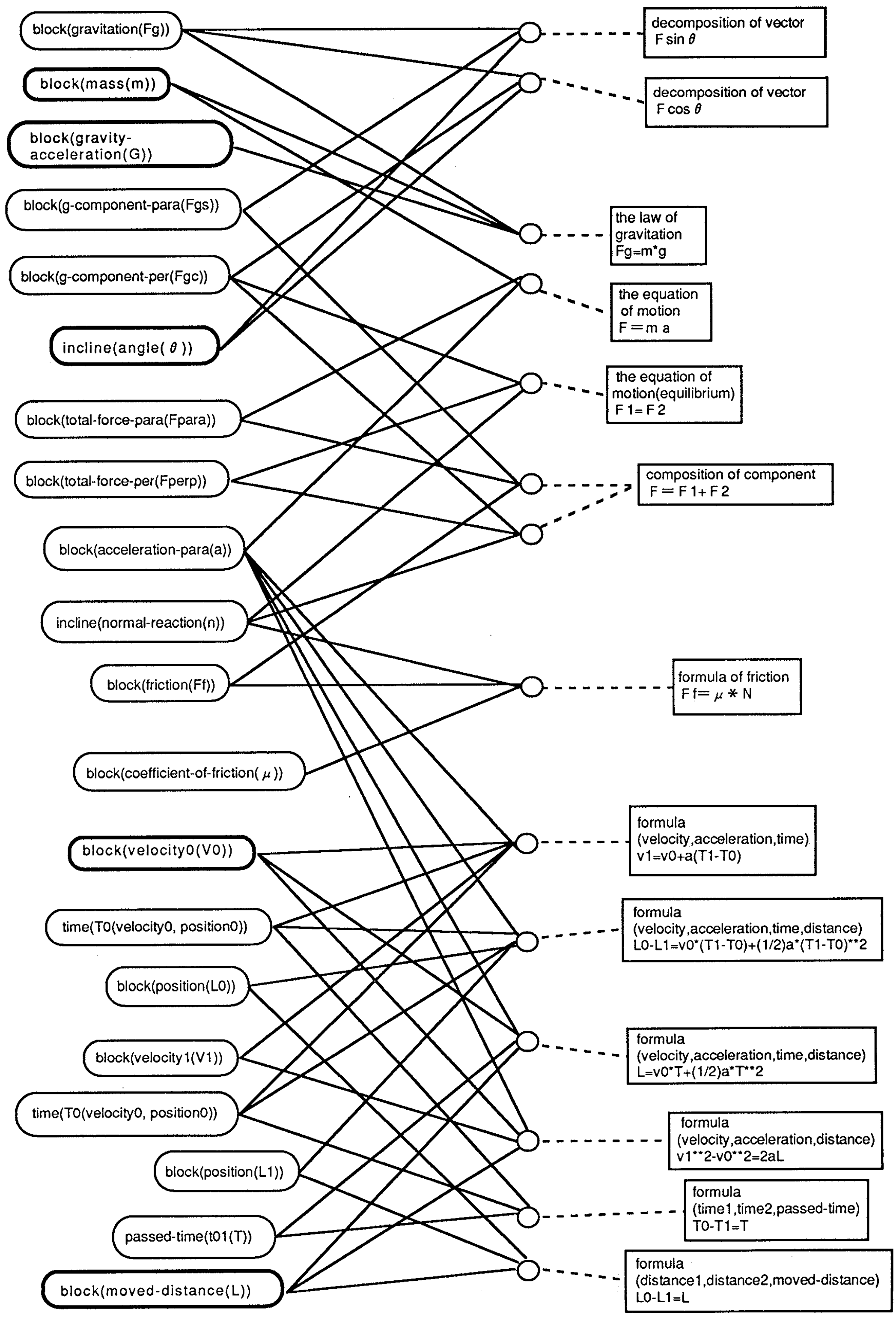


Fig. 2 Phenomenon structure.

the phenomenon attributes. The bold nodes of attributes are given or required attributes of Problem-1. The nodes on the right side are the mechanics formulas which are operational relations among the attributes. The circles indicate the existence of the relations. The solid lines connect the attributes to the relations. The relations correspond to the mechanics formulas with the broken lines.

The same mechanics formulas may be applied to different phenomena. Also, the difficulties of the problems to which the same formula should be applied are different according to the phenomena which each problem belongs to. Therefore, if the index of problems is represented only by mechanics formulas, it is impossible to set problems properly in the practice. By using the indexing framework proposed in this paper, problems can be classified by the differences of the phenomena constrained therein.

We have implemented a solution finder which finds the path from given attributes to required attributes in the phenomenon structure. The path is the solution structure. In the solution structure, the relations in the path are interpreted as procedural knowledge, that is, the inputs and outputs are specified. The solution finder and solution structure are described in Sect. 2. 3.

Currently, we have to prepare a phenomenon structure for each class of phenomena. Also, various phenomenon structures can be prepared by modifying one phenomenon structure. Therefore, it is possible to enumerate by hand a set of phenomenon structures for the problems used in some domain. However, to prepare every phenomenon structure is too hard. Therefore, we plan to realize automatic generator of phenomenon structures from surface structures based on the technique of automatic modeling in the field of qualitative reasoning [15].

2. 3 Solution Structure

A problem is defined by a set of given or required attributes on a phenomenon structure. A solution structure for the problem is a network which connects given attributes to those required. Also, in the network, the states of attributes, such as given, required, and derived must be decided and each link must have the direction which indicates the direction of value propagation. The network is referred to as solution structure. According to phenomenon attributes, given or required attributes are called first-order attributes of the problem, and derived attributes are called second-order attributes of the problem. The attributes which do not contribute to solve the problem are called zero-order attributes of the problem. The zero-order attributes can be used to generate another problem which belongs to the same phenomenon but the different solution structure. The second-order attributes are used to generate subproblems. The first- and second-order attributes which appear in solution structure, are called problem attributes.

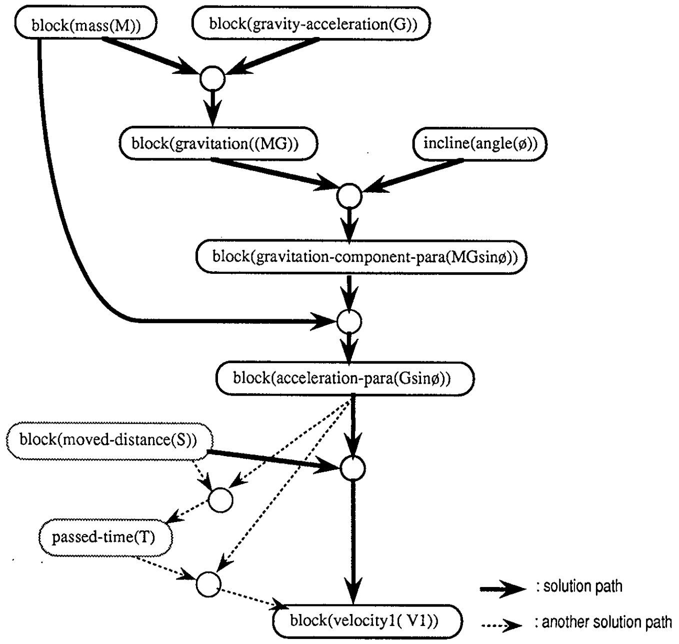


Fig. 3 Solution structure of Problem-1.

Figure 3 shows solution structure of Problem-1 shown in Fig. 1. The solution structure is regarded as a direction-supplied partial network of the phenomenon model shown in Fig. 2. In the solution structure, leaves are the given attributes and roots are the required attributes. Each circle means a mechanics formula the detail of which is omitted in Fig. 3.

The solution finder which has been implemented can generate the solution structure from phenomenon structure and a set of given or required attributes, though visualization of the solution structure as Fig. 3 has not been completed. Currently, the solution finder can solve not only the case corresponding to a linear equation with one unknown but also the case corresponding to linear equations with two unknowns. Also, it can find alternatives. The partial structure drawn by broken lines is one of the alternative solution paths on the phenomenon structure.

3. Control of Problem Sequence Based on the Indexing

3. 1 Reordering of Problem Sequence

The differences between all the problems in a problem sequence, are usually designed based on several tutoring goals. An ideal student who can understand the differences also can achieve the goals by solving the problems. However, students who can solve every problem do not always understand the differences. Also, several students fail to solve the problems. The students who have just come in problem practices

[Problem-2]
A block of mass M is put on a smooth incline quietly. The angle of the incline is ϕ and the gravity acceleration value is G.
(a) Find the acceleration of the block in parallel direction to the incline.
(b) Find the velocity of the block when it moved for a distance of S on the incline.
(c) Find the longest moved distance to the upper parallel direction on the incline when the initial velocity of the block is V to the upper parallel direction on the incline.

[Problem-3]
A block of mass M is put on a coarse incline. The angle of the incline is ϕ and the gravity acceleration value is G. The coefficient of friction between the block and the incline is μ.
(a) Find the acceleration of the block when its first velocity is zero.
(b) Find the acceleration of the block when its first velocity is V to the upper parallel direction on the incline.

[Problem-4]
A bock of mass M is put on a coarse incline quietly. The angle of the incline is ϕ and the gravity acceleration value is G. The coefficient of friction between the block and the incline is μ. The time T is required when the block moves the distance of L from starting point. Find the coefficient of friction between the block and the incline.

Fig. 4 A problem series.

usually can solve basic problems. Therefore it is very important to help them focusing on the differences. Reordering of problem sequence is a promising method to clarify the differences of problems.

The reordering can be also a means to make the student to learn topics which were not anticipated systematically in the original problem sequence since they did not correspond to the given focus. For example, a mechanical block has a characteristic nature. Therefore, to understand this nature can be relevant for solving this class of problems. If the problem sequence is designed from the viewpoint of solution structure, it is not adequate to promote better understanding of the nature of blocks. It is necessary to collect problems which deal with the block in various situations and to arrange them from the viewpoint of dealing with the block.

Figure 4 shows a problem sequence which is selected from a unit of a textbook. The unit is composed of 16 problems (a subproblem is counted as one). The problem sequence has been constituted by selecting problems which have the same configuration pattern as shown in Fig. 1(b) and by ordering them according to their original order. The generated sequence shown in Fig. 4 includes several kinds of phenomenon and solutions. Note that Problem-2b is the same as Problem-1. In this section, reordering of the problem sequence based on the indexing framework are explained.

By using the inclusion relation of solution structure, the problem sequence is reordered as shown in Fig. 5. The nodes at the end of the arrows have some elements in addition to the elements contained in the nodes at the starting point of the arrows. The tags of the arrows mean the additional elements. The solution structure of every problem includes the solution structure of Problem-2a. According to solution structure, Problem-4 is the most complex problem. Problem-2a, Problem-2b and Problem-3a are prerequisite to solve Problem-4. To solve Problem-2c and Problem-3b aren't necessary to solve Problem-4. Currently, other solutions of each problem aren't dealt with the reordering. This is one of the future issues of this research.

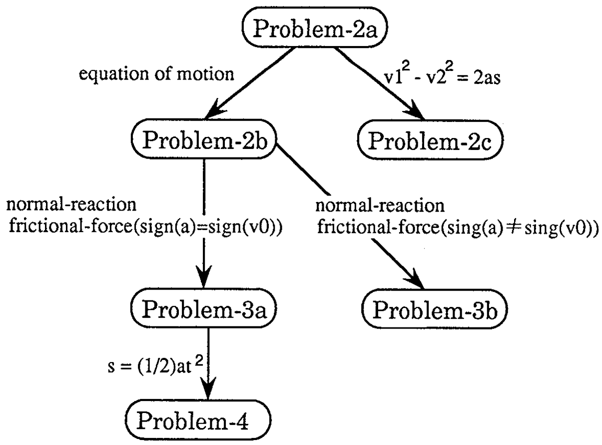


Fig. 5 Reordering by solution structure.

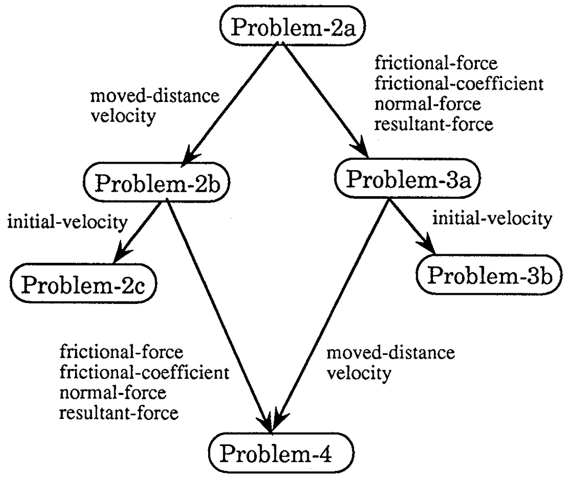


Fig. 6 Reordering by problem attributes.

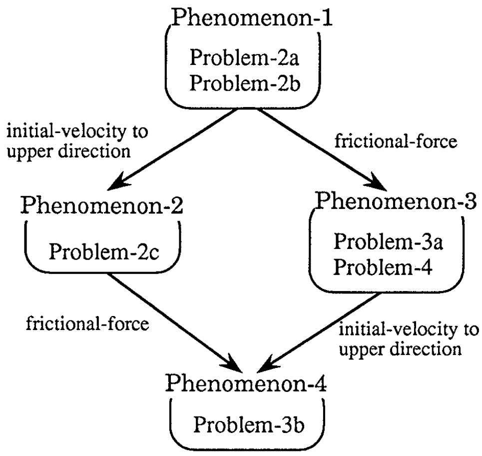


Fig. 7 Reordering by phenomenon structure.

Figure 6 shows reordering of the problem sequence based on the inclusion relation of problem attributes. In order to solve Problem-2b, students have to deal with moved-distance and velocity in addition to the set of attributes which have to be dealt with in Problem-2a. Problem-2c needs initial-velocity in addition to the attributes in Problem-2b. By using the phenomenon structure, the problem sequence is reordered as shown in Fig. 7. The relations between phenomenon structure must be prepared. Problems are reordered along the relations. Phenomenon-structure-1 (we call it Phenomenon-1) includes Problem-2a and Problem-2b. Both Problem-3a and Problem-4 belong to the same phenomenon Phenomenon-3 which entails frictional force in addition to Phenomenon-1, although the given or required attributes of the two problems are different.

Currently, we have implemented a module which can retrieve problems by using the description of the indexing. The module uses a keyword which is described with the notation of the indexing, such as solution structure, problem attributes and so on, and can retrieve problems which have index including the keyword. It can also arrange the problems by using the inclusion relation, such as solution structure, problem attributes, phenomenon attributes and others. The problem sequence and the difference of each other can be generated as a list structure, but the visualization has not been realized.

Also, reordering by using partial structure hasn't been completed. It is possible to retrieve problems which include a partial structure. Therefore, the remaining structures must be estimated to reorder. Currently, the inclusion relation is the only criterion for estimation. Therefore, reordering cannot always be carried out adequately. This is one of the important future issues.

3. 2 Simplifying of Problems

Simplifying of a problem is important as one of adaptive arrangement of problems. The simplifying of a problem is often employed when a student fails to solve a problem. There are two kinds of approaches to simplify a problem, one is simplification of solution structure and the other is simplification of phenomenon structure. The simplification of solution structure means to derive subproblem from an original problem by setting up subgoals or by giving some attributes which are derived in solving the original problem. A solution structure includes the derived attributes, in addition to the given or required attributes. By changing several derived attributes to given or required ones, a problem which has a partial solution structure of original one can be generated. The problem should be solved in the problem solving process of the original one. Therefore, it is a subproblem. The subproblem which is generated by changing derived attributes to given ones, is referred to as a top-down subproblem. The subproblem which is generated by changing derived attributes to required ones, is referred to as a bottom-up subproblem. These subproblems are used to help students who cannot solve original one. For example, in the solution structure of Problem-2b shown in Fig. 3, if the value of gravitation-component which is a derived attribute is changed to a required attribute, Problem-2a becomes a bottom-up subproblem of Problem-2b. A top-down subproblem of Problem-2b is the problem in which both moved-distance and acceleration are given and velocity is required.

Phenomenon simplification means to change several problem attributes to default values in phenomenon structure. For example, the default value of initial velocity is zero. When the value becomes zero, some relations related it are simplified. By the phenomenon simplification, considerable attributes in the problem are reduced. The simplification is useful to teach specific concepts in a problem to a student when he/she failed to solve the problem. It is also useful to identify the concepts which are the cause of his/her failure. For example, assume that a student failed to solve Problem-3b because he/she cannot deal with frictional force. Phenomenon-3 is simpler than Phenomenon-4 in the respect of the frictional force. In this case, Problem-3a is one of the problems which are generated phenomenon simplification from Phenomenon-4 to Phenomenon-3. Problem-3a is better to learn frictional force than Problem-3b, because Problem-3b entails more attributes than Problem-3a which are additional to the tutoring targets. Phenomenon-2 is also simpler than Phenomenon-4 concerning frictional force. If the student fails to solve Problem-3b because of frictional force, the problem which is modified into Phenomenon-2 could be solved by the student. Currently, the relation of simplification between phenomenon structures must be manually prepared in order for the system to generate the index which represents a simplified problem. The function of the modification of problem sentences has not been completed.

4. Concluding Remarks

We have described an indexing framework of mechanics problems for ITS. In the domain of mechanics, to understand various concepts used in problems is important as well as to understand solution methods. The indexing framework is composed of three facets: (1) surface structure, (2) phenomenon structure, and (3) solution structure. Based on the indexing framework, problems have been classified from these viewpoints of characteristic concepts in the domain of mechanics, and the relations between any two problems have been clarified. Therefore, the indexing framework contributes to realize adaptive arrangement of problem sequences. This paper has also described on reordering problem sequences and simplifying problems based on the indexing. These functions have been implemented except for the part of the interface. Because the interface for communication with students and for acquisition of problem indices, are very important, to build such interface is one of our urgent issues.

Another goal of ours is to realize an advanced learning by practice environment with control of problem sequences based on indexing by using the functions described in the present paper. To realize the goal, a student model is indispensable to provide information enabling the system to decide which reordering or simplifying is appropriate for each student [16]-[19]. We are planning to build a student model based on the description of the indexing.

References

[1] Sleeman, D. and Brown, J. S., *Intelligent Tutoring Systems*, Academic Press, 1982.

[2] Wenger, E., *Artificial intelligence and tutoring systems*, Morgan Kaufmmann Publishers, Los Altos, 1987.

[3] Hirashima, T., Nakamura, Y., Ikeda, M., Mizoguchi, R. and Toyoda, J., "A Cognitive Model for ITS," in Eds. Lewis, R. and Otsuki, S., *Advanced Research on Computer in Education,* pp. 211-217, North-Holland, 1991.

[4] Hirashima, T., Niitsu, T., Kashihara, A. and Toyoda, J., "An Indexing Framework for Adaptive Setting of Problems in ITS," *Proc. of AI-ED93*, pp. 90-97 (1993).

[5] Schank, R. C., "Teaching Architectures," Northwestern Univ. Institute for the Learning Science, TR # 3, 1990.

[6] Hirashima, T., Kashihara, A. and Toyoda, J., "Providing Problem Explanation for ITS," in Eds. Frasson, C., Gauthier, G. and McCalla, G. I., *Intelligent Tutoring System,* Lecture Notes in Computer Science 608, pp. 78-83, Springer-Verlag, 1992.

[7] VanLehn, K., "Learning One Subprocedure per Lesson," *Artificial Intelligence*, vol. 31, no. 1, pp. 1-40, 1987.

[8] Mizoguchi, R. and Ikeda, M., "A Generic Framework for ITS and Its Evaluation," *Proc. of ARCE,* pp. 303-312, 1990.

[9] Ikeda, M. and Mizouchi, R., "Design of a Generic Framework for ITS," *Proc. of ITS-88,* pp. 82-89, 1988.

[10] Larkin, J. H., McDermott, J., Simon, D. P. and Simon, H. A., "Model of Competence in Solving Physics Problems," *Cognitive Science,* vol. 4, pp. 317-345, 1980.

[11] Chi, M. T. H., Feltovich, P. J. and Glaser, R., "Categorization and Representation of Physics Problems by Experts and Novices," *Cognitive Science,* vol. 5, pp. 121-152, 1981.

[12] Kahney, H., *Problem Solving : A Cognitive Approach,* Open University Press, 1986.

[13] Hardiman, P. T., Dufresne, R. and Mestre, J. P., "The relation between problems categorization and problem solving among novices and experts," *Memory & Cognition,* vol. 17, pp. 627-638, 1989.

[14] Durfresne, R. J., Gerace, W. J., Hardiman, P. T. and Mestre, J. P., "Constraining Novices to Perform Expert-like Problem Analyses : Effects on Schema Acquisition," *Journal of the Learning Science,* vol. 2, no. 3, pp. 307-331, 1992.

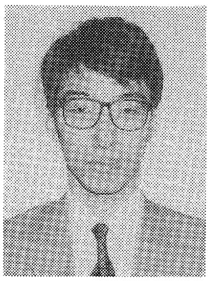
[15] Forbus, K. D. and Falkenhainer, B., "Self-Explanatory Simulations : An integration of qualitative and quantitative knowledge," *AAAI-90,* pp. 380-387, 1990.

[16] McCalla, G. and Greer, J., (Eds.), "Special Issue on Student Modelling," *Jl of Artificial Intelligence in Education,* vol. 3, no. 4, 1992.

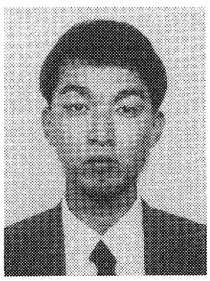
[17] Matsuda, N. and Okamoto, T., "Student Model Diagnosis for Adaptive Instruction in ITS," in Eds. Frasson, C., Gauthier, G. and McCalla, G. I., *Intelligent Tutoring System,* Lecture Notes in Computer Science 608, pp. 467-474, Springer-Verlag, 1992.

[18] Takeuchi, A. and Otsuki, S., "EXPITS : An Experimental Environment on ITS," in Eds. Frasson, C., Gauthier, G. and McCalla, G. I., *Intelligent Tutoring System,* Lecture Notes in Computer Science 608, pp. 124-131, Springer-Verlag, 1992.

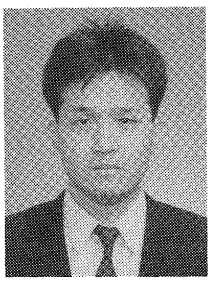
[19] Kono, Y., Ikeda, M. and Mizoguchi, R., "To Contradict is Human-Student Modeling of Inconsistency," in Eds. Frasson, C., Gauthier, G. and McCalla, G. I., *Intelligent Tutoring System,* Lecture Notes in Computer Science 608, pp. 451-458, Springer-Verlag, 1992.



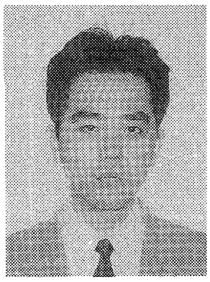
Tsukasa Hirashima graduated in 1986 from the Dept. of Appl. Phys., Fac. Eng., Osaka University, where he obtained a Dr. of Eng. degree in 1991 and became an Assistant at the Inst. Sci. Indust. Res., Osaka University. Presently, he is engaged in research on artificial intelligence, especially in ITS. He is a member of the Inf. Proc. Soc. Jap.; Soc. Artif. Intel.; and Educ. Tech. Soc.



Toshitada Niitsu graduated in 1991 from the Dept. of Appl. Phys., Fac. Eng., Osaka University, where he obtained a Master's degree in 1993 and affiliated with Osaka Gas Co., Ltd. As a graduate student, he engaged in research on ITS. He is a member of the Soc. Artif. Intel.



Kentaro Hirose graduated in 1992 from the Dept. of Appl. Phys., Fac. Eng., Osaka University, and is presently a graduate student. He is engaged in research on ITS.



Akihiro Kashihara Education: Tokushima University, B.S. (1987), M.S. (1989); Osaka University, D.Eng. (1992). Academic appointment: Institute of Scientific and Industrial Research, Osaka University, research associate (1992). Research interests: intelligent tutoring systems, intelligent interfaces, program understanding. Memberships: Information Processing Society of Japan; Japanese Society for Artificial Intelligence; and Japan Society for CAI.

Jun'ichi Toyoda graduated in 1961 from the Dept. of Comm. Eng., Fac. Eng., Osaka University, where he obtained a Dr. of Eng. degree in 1966 and became an Assistant in 1966 and an Assoc. Prof. in 1969 on the Fac Eng. Sci. He became a Professor in 1982 at the Inst. Sci. Indust. Res., Osaka University. Presently, he is engaged in research on artificial intelligence, especially in ITS. He is a member of the Inf. Proc. Soc. Jap.; Soc. Artif. Intel.; and Jap. Soc. Cogn. Sci.