The Effect of Problem Sequence on Students' Conceptual Understanding in Physics

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Abstract. The effect of problem sequence on students' understanding in elementary mechanics is empirically examined. We used two types of problem sequences: and surface-blocked sequence. In the former, problems of which superficial feature is different but solution is the same are adjacent, while in the latter, problems of which superficial feature is similar but solutions are different are adjacent. Our hypotheses were: (1) Students who learned with structure-blocked sequence show better performance in solving simple problems because it would train students how to apply a solution in various situations. (2) Students who learned with surface-blocked sequence show better performance in solving complex problems because it would give students an exercise in choosing appropriate solution depending on the situation. (3) The effect of surface-blocked sequence appears more clearly when students are aware of the structure of problems. The results of experiment suggested our hypotheses are true.

Keywords: Science education · Effect of problem sequence · Conceptual understanding · Semantics of constraints · Mechanics

1 Introduction

In science education, it is an important goal for students to acquire the ability to make an appropriate model for a given task. They need to identify the intrinsic features of the system and its behavior they are considering, and formulate the relations of the features. We call such ability 'conceptual understanding.'

However, conventional problem practice hardly helps students reach such an understanding. Students often superficially read the solution of a problem and apply it wrongly to others without understanding the model [1, 2]. This is mainly because students tend to represent a problem based on its superficial features (called surface structure) rather than its structural features (called physical structure) [3]. For example, after a student solved 'a block on a slope' problem with 'Newton's 2nd law,' she/he

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often tries to solve another ‘a block on a slope’ problem with the same law even if it should be solved with ‘conservation of energy.’

In order to reach conceptual understanding, students should learn to infer the physical structure of problems from the surface structure, to which physical laws are applicable. Usually, students must do so by induction with a huge number of various problems because most of such expertise is implicit knowledge and hard to be taught explicitly [2]. This is not an easy task for students.

Therefore, it is very important to design a set of problems and sequence them appropriately so as to promote students’ inductive learning [4]. For this purpose, we previously proposed a framework for indexing physical problems, with which one can design and sequence a set of problems systematically [5]. Its key technology is called ‘Semantics of Constraints (SOC)’ which is the conceptualization of experts’ model-making process in physics. By using SOC, the physical meaning of constraints in a model and the assumptions behind them can be explicitly represented. That is, the surface/physical structure of a problem becomes explicit. Therefore, the difference of surface/physical structure between problems can be clearly described, which helps in sequencing a set of problems systematically. The question here is: What kind of sequences are effective?

In this paper, we report the result of the preliminary experiment in which how the problem sequences generated by using our framework effect on students’ conceptual understanding in physics was examined. We used two types of problem sequences: structure-blocked sequence and surface-blocked sequence [6]. In the former, the problems which have different surface structures but the same/similar physical structures are adjacent (for example, two problems both of which are solved with ‘Newton’s 2nd law’ are adjacent even if one is ‘a block on a slope’ problem and the other is ‘a block connected to a spring on a floor’ problem). In the latter, the problems which have the same/similar surface structures but different physical structures are adjacent (for example, two ‘a block on a slope’ problems are adjacent even if one is solved with ‘Newton’s 2nd law’ and the other is solved with ‘the law of conservation of energy’). We have two hypotheses: (1) Students who learned with structure-blocked sequence show better performance in solving simple problems (in which applying a physical law is sufficient) than those who learned with surface-blocked sequence. This is because the formers continue to apply a solution in various superficially different problems and fix how to apply it. (2) Students who learned with surface-blocked sequence show better performance in solving complex problems (in which combining multiple physical laws is necessary) than those who learned with structure-blocked sequence. This is because the formers encounter superficially similar problems and have to choose appropriate solution depending on the situation. Additionally, since the latter learning is more difficult, the effectiveness of surface-blocked sequence appears more clearly as to students who are aware of the structure of problems. We conducted an experiment to verify our hypotheses, and the result suggested they are true. The result would be the basis of sequencing physical problems adaptively to individual student in computer-based learning.

2 Hypotheses

2.1 Related Work

The effect of sequence of problems has been studied mainly from the viewpoint of transfer by analogy [7]. When a student tries to solve a new problem (target), she/he retrieves a problem she/he previously solved (base), and maps the elements of the base onto the target to generate a solution of the target. In this process, it is important to retrieve a base problem which is structurally similar to the target problem. If the similarity is only superficial, mapping of the elements fails to generate a solution. Therefore, how a set of problems are sequenced which are structurally and/or superficially similar to each other would greatly influence learning.

On this issue, Scheiter and Gerjets presented two hypotheses: Transfer hypothesis and near-miss hypothesis [6]. According to the former, learning with structure-blocked sequence (see Sect. 1) is more effective because surface-blocked sequence (also see Sect. 1) makes a student retrieve an inappropriate previous problem as the base. A superficially similar problem is easily retrieved but its solution isn't necessarily applicable to the target. According to the latter, learning with surface-blocked sequence is more effective because a small difference of superficial features would focus the intrinsic difference of structural features. Additionally, it was predicted that for students who were aware of the structure of problems, structure-blocked sequence is more effective because they can easily activate the structurally same solution as the current problem in such sequence, and that surface-blocked sequence is less effective because the solution of previous problems which is inappropriate for the current problem confuses them. These hypotheses were verified through experiments.

2.2 Our Hypotheses

In this paper, aiming at physics domain (mainly elementary mechanics), we examine which of surface-block or structure-block sequence is more effective for which of students who are or aren't aware of the structure of problems.

The domain of Scheiter and Gerjets [6] was word problem of arithmetic. The 'superficial feature' of problems was the 'cover story' which was the situation such as 'two electricians repair a lamp' and 'two people travels a distance toward each other.' The 'structural feature' of problems was the solution procedure with which problems were solved, such as 'work' (calculating the amount of work) and 'motion' (calculating the amount of motion). Problems were categorized by solution and each category had a typical cover story. Some problems' cover story corresponds to their solution (it is typical in their category), while some problems' cover story doesn't (it isn't typical in their category). Students had to identify the solution of problems without being confused by their cover story.

In physics, on the other hand, the matter is different. The superficial feature in mechanics problems is the components of the system in consideration and their spatial configuration. Unlike word problem, a small difference of situation doesn't necessarily cause a large difference of solution (e.g., a smooth floor is changed to be rough).

What causes large change of solution is the 'query' which is typically the amount to be calculated (e.g., as for the same system, Newton's second law is necessary for the value of an acceleration, while the law of conservation of energy is necessary for that of a velocity). Therefore, it is predicted that the similarity of superficial feature in mechanics problems less influences students than that in word problems (additionally, according to our experiment, not a few students can get aware of the difference of queries). Rather, surface-blocked sequence might give students an exercise in choosing appropriate solution depending on the situation, of which effect would appear in solving complex problems (in which multiple physical laws had to be combined). On the other hand, structure-blocked sequence might train students how to apply a solution in various situations. In spite of the superficial difference of problems, they could focus on the queries and less confused. This effect would appear in solving simple problems (in which applying a physical law is sufficient). Of course, since it is difficult to learn how to choose appropriate solutions in various situations (in our term, it is 'conceptual understanding'), the effect of surface-blocked sequence appear more clearly when students are aware of the structure of problems.

Therefore, our hypotheses are as follows: (1) Students who learned with structure-blocked sequence show better performance in solving simple problems (in which applying a physical law is sufficient) than those who learned with surface-blocked sequence. (2) Students who learned with surface-blocked sequence show better performance in solving complex problems (in which combining multiple physical laws is necessary) than those who learned with structure-blocked sequence. (3) The effect of surface-blocked sequence appears more clearly as to students who are aware of the structure of problems.

We conducted an experiment to verify our hypotheses. We designed both sequences of problems based on SOC framework (which means the learning effect revealed in this experiment can be computationally controlled in intelligent educational systems). Additionally, for making students aware of the structure of problems, we used SOC-based explanation [5]. It is the explanation about solutions of physical problems in which how to make the model necessary for solving a problem is shown focusing on why physical laws can applied in the situation (modeling assumptions are explicitly explained), and about relations between solutions in which how and why model/solution changes when the situation/assumptions is/are changed. We previously verified that SOC-based explanation facilitates students' awareness of the structure of problems and conceptual understanding [5]. The design, results and implication of the experiment are presented in the next section.

3 Experiment

3.1 Design

We conducted an experiment to verify our hypotheses. The purpose was to examine which sequence of problems promotes students' conceptual understanding more effectively under what conditions.

Subjects: Twenty-six undergraduates whose majors are engineering participated in.

Instruments: (1) Two sets of problems in elementary mechanics: They were called 'problem set 1 (PS-1)' and 'problem set 2 (PS-2).' Each set included fifteen problems of various surface/physical structures. Problems might have similar situations but different solutions, or have different situations but similar solutions. The sets had no common problem. (2) Usual explanation about the solutions of eleven problems in PS-1: The calculation of the required physical amount from the given ones was mainly explained. (3) SOC-based explanation about the solutions of the same problems as usual explanation. In addition to the solution of each problem, the differences between problems were explained about eight pairs of problems which had similar surface/physical structures. (4) A set of three worked-examples (called 'basic problems') which could be solved by applying 'Newton's second law', 'conservation of energy' and 'balance of forces' respectively. (5) Two sequences of problems which were called 'surface-blocked sequence' and 'structure-blocked sequence.' Each sequence included nine problems which were divided into three blocks. In surface-blocked sequence, each block included three problems which were superficially similar but had to be solved by applying different solution. In structure-blocked sequence, each block also included three problems which were superficially different but could be solved by applying the same solution. All problems could be solved by applying one of the three laws used in basic problems. (6) A set of three problems (called 'complex problems') each of which had to be solved by applying two of the three laws used in basic problems.

Procedure: In the first week, subjects were given PS-1 and asked to group the problems into some categories based on some kind of 'similarity' they suppose (any number/size of categories were allowed), then asked to label each category they made (called 'categorization task 1'). After that, they were asked to solve eight problems in PS-1 (called 'pre-test'). After a week, the subjects were divided into four groups: A1, A2, B1 and B2. A1 and A2 included six subjects respectively, and the average scores of both groups in pre-test were made equivalent. The subjects of these groups were given SOC-based explanation and asked to learn it (in order to make them aware of the structure of problems). B1 and B2 included seven subjects respectively, and the average scores of both groups in pre-test were made equivalent. The subjects of these groups were given usual explanation and asked to learn it (they wouldn't get aware of the structure of problems). Then the subjects of all groups were given basic problems and asked to learn them. After that, the subjects of A1 and B1 were given surface-blocked sequence while those of A2 and B2 were given structure-blocked sequence, and asked to solve the problems in the given order (called 'sequence-exercise'). In the third week, all subjects were given complex problems and asked to solve them (called 'complex-test'). After that, by using PS-2, 'categorization task 2' was conducted for all subjects in the same way as above. Finally, they were asked to solve eight problems in PS-2 (called 'post-test').

Measure: The awareness of the structure of problems was measured with the result of categorization tasks. The categories, their 'frequencies' (number of problems accounted for) and the time required were examined. The conceptual understanding was measured with the scores of tests and exercise. The ability to apply a simple solution (applying a physical law is sufficient) was measured with the scores of pre-/post-tests and sequence-exercise. The ability to apply a complex solution (applying two physical law is necessary) was measured with the scores of complex-test. The effect of sequence of problems was measured with the difference of the scores of tests and exercise between A1 and A2, and between B1 and B2.

3.2 Results

The result of categorization task 1 is shown in Table 1 (for B1 and B2) and Table 2 (for A1 and A2). Most of the subjects categorized problems based on the similarity of their superficial features, such as the components of the system (e.g., inclined plane, spring), the figures of motion (e.g., circular motion, free fall). Additionally, all subjects finished the task within thirteen minutes. The result of categorization task 2 is shown in Table 3 (for B1 and B2) and Table 4 (for A1 and A2). Many subjects who learned with usual explanation still categorized problems based on the similarity of their superficial features, while many subjects who learned with SOC-based explanation became to categorize problems based on the similarity of their structural features, that is, the dominant laws of problems (e.g., Newton's second law, balance of forces, conservation of energy). Additionally, all subjects of B1 and B2 finished the task within thirteen minutes again, while the subjects of A1 and A2 required from nine to thirty-five minutes. These results indicate that the subjects of B1 and B2 weren't aware of the structure of problems throughout the experiment, while those of A1 and A2 got aware of the structure of problems before sequence-exercise (the increase of the time

Table 1. Categories in task 1 (B1 and B2)

	Number of subjects using category labels (N_1=14)	Average size of category (N_2=15)	Number of problems accounted for ($N=N_1 \times N_2$=210)	Number of problems wrongly accounted for (N^*=210)	Number of problems correctly accounted for (N^C=N-N^*)
Free fall	**11**	**4.1**	**45**	**1**	**44**
Inclined planes	**9**	**3.3**	**30**	**1**	**29**
Springs	**10**	**2.6**	**26**	**1**	**25**
Circular motion	**10**	**1.9**	**19**	**0**	**19**
String/tension	**7**	**2.1**	**15**	**0**	**15**
Collision	**7**	**1.6**	**11**	**0**	**11**
Accelerated motion	2	5.5	11	2	9
Linear motion	1	3	3	0	3
Second law	1	2	2	0	2
Pulleys	1	2	2	0	2
Friction	1	2	2	0	2
Balance of forces	1	3	3	2	1
Impulse	1	2	2	2	0
Others	13	4.4	57	0	57

Table 2. Categories in task 1 (A1 and A2)

	Number of subjects using category labels (N_1=12)	Average size of category (N_2=15)	Number of problems accounted for ($N=N_1×N_2$=180)	Number of problems wrongly accounted for (N^*=180)	Number of problems correctly accounted for (N^C=N-N^*)
Free fall	**7**	**4**	**28**	**0**	**28**
Springs	**6**	**2.3**	**14**	**0**	**14**
Inclined planes	**3**	**3.7**	**11**	**0**	**11**
Gravity	**1**	**11**	**11**	**0**	**11**
Circular motion	5	1.8	9	1	8
Balance of forces	4	4.8	19	11	8
Accelerated motion	2	3.5	7	0	7
Linear motion	2	3.5	7	0	7
Conservation of energy	4	2	8	2	6
Collision	2	2	4	0	4
Second law	3	2.7	8	4	4
Pulleys	2	1.5	3	0	3
Momentum	1	2	2	0	2
Centripetal/centrifugal force	1	2	2	1	1
Others	5	9.4	47	0	47

Table 3. Categories in task 2 (B1 and B2)

	Number of subjects using category labels (N_1=14)	Average size of category (N_2=15)	Number of problems accounted for ($N=N_1×N_2$=210)	Number of problems wrongly accounted for (N^*=210)	Number of problems correctly accounted for (N^C=N-N^*)
Springs	**9**	**3.7**	**33**	**0**	**33**
Inclined planes	**6**	**5**	**30**	**1**	**29**
Second law	**7**	**3.6**	**25**	**3**	**22**
Pendulum	**8**	**2.5**	**20**	**4**	**16**
Pulleys	**4**	**3.8**	**15**	**0**	**15**
Balance of forces	**2**	**7**	**14**	**1**	**13**
String/tension	**6**	**2.5**	**15**	**3**	**12**
Circular motion	7	1.6	11	2	9
Friction	5	1.4	7	0	7
Conservation of energy	2	4.5	9	3	6
period	3	1	3	0	3
Linear motion	1	2	2	0	2
Collision & momentum	1	1	1	0	1
Free fall	1	3	3	3	0
Others	7	5.1	36	0	36

Table 4. Categories in task 2 (A1 and A2)

	Number of subjects using category labels (N_1=12)	Average size of category (N_2=15)	Number of problems accounted for ($N=N_1 \times N_2$=180)	Number of problems wrongly accounted for (N^*=180)	Number of problems correctly accounted for (N^C=N-N^*)
Second law	**10**	**4.4**	**44**	**5**	**39**
Conservation of energy	**7**	**4.3**	**30**	**4**	**26**
Balance of forces	**6**	**3.7**	**22**	**2**	**20**
Springs	**4**	**4**	**16**	**0**	**16**
Inclined planes	2	3.5	7	0	7
Pulleys	2	3.5	7	0	7
Circular motion	4	1.3	5	0	5
Accelerated motion	1	4	4	1	3
Linear motion	1	3	3	0	3
Conservation of momentum	4	2	8	5	3
Simple harmonic/ periodic motion	3	1	3	0	3
Inertial force	2	1.5	3	0	3
Pendulum	2	1.5	3	0	3
Collision	2	1	2	0	2
String/tension	1	2	2	0	2
Friction	1	1	1	0	1
Impulse	1	1	1	1	0
Others	3	4.3	13	0	13

required suggests the subjects of A1 and A2 inferred the physical structure from surface structure).

The average scores in pre-/post-tests, complex-test and sequence-exercise are shown in Table 5. In pre-test, there was significant difference of average scores neither between A1 and A2 nor between B1 and B2 (t-test $p > .10$). In post-test, the average score of A1 was higher than that of A2, and the average score of B1 was higher than that of B2 though there was no significant difference (t-test $p > .10$). In sequence-exercise, the result was the same. In complex-test, on the other hand, the average score

Table 5. Average scores of tests and exercise

Average score (full mark)		Pre-test (55)	Sequence-exercise (60)	Complex-test (30)	Post-test (55)
Aware of structure	A-1: structure-blocked (N = 6)	33.3	56.7	13.3	49.5
	A-2: surface-blocked (N = 6)	29.7	55.7	21.3	40.0
Not aware of structure	B-1: structure-blocked (N = 7)	23.6	43.3	6.7	29.7
	B-2: surface-blocked (N = 7)	23.6	38.0	9.1	27.7

of A2 was higher than that of A1, and the average score of B2 was higher than that of B1. Additionally, there was significant difference between the average score between A1 and A2 (t-test $p < .05$).

The implication of these results is as follows. The subjects who learned with structure-blocked sequence showed better performance in sequence-exercise and post-test than those who learned with surface-blocked sequence whether they were aware of the structure of problems or not. On the other hand, the subjects who learned with surface-blocked sequence showed better performance in complex-test than those who learned with structure-blocked sequence whether they were aware of the structure of problems or not. The difference was more clear when students were aware of the structure of problems. These facts suggest our hypotheses are true: In physics, structure-blocked sequence is more effective in fixing how to apply a solution, so students show better performance in solving simple problems (in which applying a physical law is sufficient). On the other hand, surface-blocked sequence is more effective in learning to apply different solutions depending on the situation, so students show better performance in solving more complex problems (in which combining multiple physical laws is necessary). Since the latter learning is more difficult, the effectiveness of surface-blocked sequence appears clearer as to students who are aware of the structure of problems. Of course, the above implication is only suggested because in most cases there was no significant difference. It is necessary to confirm the validity of our hypotheses in additional experiment with more number of subjects.

4 Concluding Remarks

In this paper, we examined the effect of the sequence of problems in acquiring conceptual understanding in physics. Based on the idea that the relation between superficial and structural features in physics problems is different from that in word problems, we set two hypotheses. Through an experiment, our hypotheses were suggested to be true. It is our important future work to conduct additional experiment with more number of subjects to confirm our hypotheses.

As another approach to improve conceptual understanding of physics, we have investigated the functions to diagnose and generate feedback for correction of misconception [8, 9]. Influence of the sequence of problems to the misconceptions, effectiveness to correct them, and the way to combine these methods are also important research issues.

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