Sustained Effects of Solving Conceptually-scaffolded Synthesis Problems

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Abstract. Students commonly have difficulty with "synthesis problems", which require a combination of typically two concepts that are taught separately in different chapters and/or at significantly different times during a course. One reason for this is that students frequently rely on a formula-based approach, beginning by searching for mathematical equations or worked examples which often do not exist. We employed a guided scaffolding method to induce students to employ a more effective problem-solving approach by first searching for fundamental concepts. This method includes a sequence of two conceptually-based multiple-choice questions that have similar deep structure as the synthesis problem, and an explicit instruction to remind students to make connections between the synthesis problem and these conceptual questions. We report our findings on the sustained effects of repeated training using conceptually-scaffolded synthesis problems. In the last 2 weeks of the 2009 fall quarter, we repeatedly provided 3 groups of students with different training using scaffolded synthesis problems, un-scaffolded synthesis problems, or traditional textbook problems. Four days after the training, all students took a common final examination containing a synthesis problem without scaffolding. Results show that repeated training with scaffolded synthesis problems rendered the highest success in students' correctly identifying and applying fundamental concepts for solving this problem.

Keywords: Conceptual scaffolding, synthesis problem, problem solving.
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INTRODUCTION

A central goal of introductory physics education is to cultivate proficient problem solving skills among students. Literature on novice-expert differences casts light on effective physics problem solving [1-7]. Physics is a hierarchically structured domain; a large number of phenomena can be described by a small number of fundamental concepts. Relying on these fundamental concepts, experts often solve a problem by first searching for its underlying deep structure and then performing a series of progressively detailed qualitative analyses [1-5]. Conversely, typical students frequently begin by seeking formulas and equations to perform "plug and chug" without identifying underpinning concepts [1-5]. As a result, they frequently fail to apprehend the problem even after obtaining a correct numerical answer.

Traditional textbook problems have an important influence on how students shape their problem solving patterns. End-of-chapter problems often are localized, addressing topics only covered in single chapters. Students using "plug-and-chug" can have a high success rate and hence are regularly rewarded for their formula-based approach. Further, studies show that even after solving a thousand textbook problems, student knowledge learned from different chapters at different times remains largely disconnected [8].

In an attempt to militate against students' formula-based problem solving approach, we designed and implemented synthesis problems that combine topics broadly separated in the teaching timeline [see Fig.1(c) for example]. These problems cannot be easily solved by "plug-and-chug" using locally introduced formulas [9]. Our hypothesis was that with repeated exposure to synthesis problems, students might recognize that searching for underlying concepts would require less effort than searching entire textbooks for relevant formulas. If this hypothesis is valid, using synthesis problems can become an important strategy in the physics classroom.

To encourage students to focus on underlying concepts, we provided a sequence of two conceptually-based multiple-choice questions, with each containing one of the two concepts synthesized in the subsequent problem. Students first answered the two multiple-choice questions, and then were explicitly instructed that the following synthesis problem might be related to the previous concept questions and they should search for the underlying connections. However, students were not told what the connections were; they had to find out this information by themselves. Fig.1 shows a sample sequence. Here the synthesis problem combines energy and angular momentum conservation laws, two topics that are introduced respectively in mid- and late stages of our introductory mechanics course. We hypothesized that the conceptual scaffolding would help students to recognize the conceptual structure of the problem, which in turn would help them to achieve a successful solution.

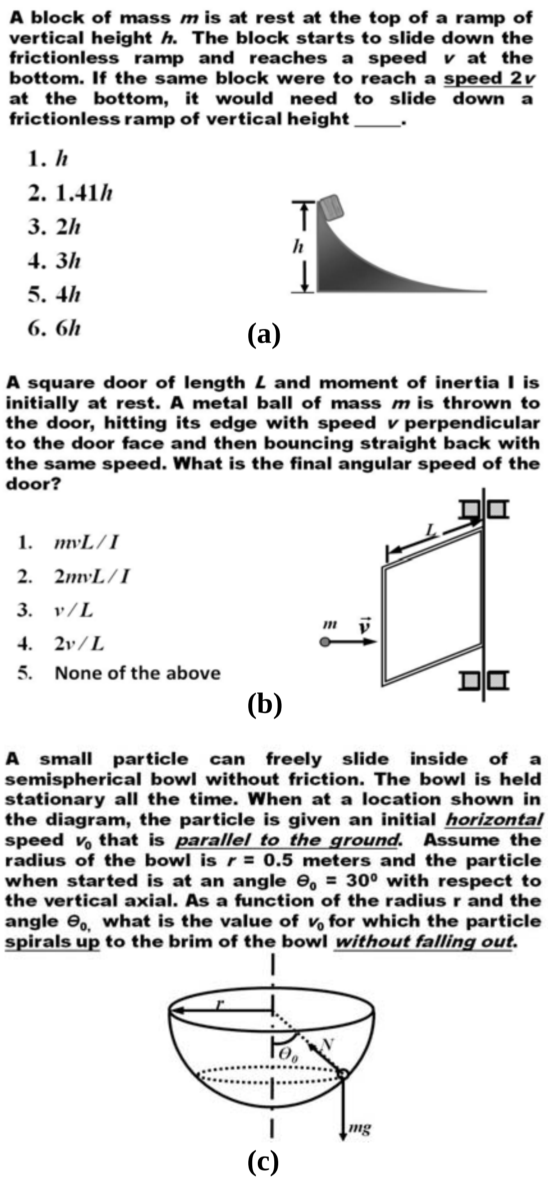


Figure 1 A sample sequence: (a) and (b) are two conceptually-based multiple-choice questions; (c) is a synthesis problem.

RESEARCH QUESTIONS

Our previous work [9] has shown that students had great difficulty solving synthesis problems if no guidance was provided. They often invoked ineffective strategies (categorized into formula search, pattern match, or random search) as an initial attempt. Using guided conceptual scaffolding not only prompted students to begin by looking for underlying concepts but also facilitated their proper application of these concepts. Conversely, direct cueing (a hint explicitly telling students what concepts to use) was useful for triggering students to start with the pertinent concepts but could not aid students making a meaningful expansion of these concepts.

Based on this work, we initiated a research design to answer the following questions:

(1) What are the sustained effects of using scaffolded synthesis problems, i.e. what can we observe after the scaffolding is removed?

(2) After receiving the repeated training, how do students perform on topics that are not covered in training, i.e. are they able to make cross-topic transfer in solving synthesis problems?

METHODOLOGY

We conducted a large-scale study in the last 2 weeks of the fall 2009 quarter with 3 parallel classes of a calculus-based introductory mechanics course. These classes shared the same course syllabus, recitations, labs, homework, quizzes, midterm exams and final exam. Each class was randomly assigned into one of the 3 treatment groups: Scaffolded Synthesis Group (SSG), Unscaffolded Synthesis Group (USG), and Control Group (CG) with 92, 82 and 90 students in each. Students in the SSG always received conceptual scaffolding prior to solving each synthesis problem; students in the USG always directly solved the same synthesis problem without receiving conceptual scaffolding; and CG students each time worked on a pair of textbook-like single-concept problems with equivalent topic coverage. All groups consistently received repeated training for the last 2 weeks of the quarter (with one being over Thanksgiving weekend) in various learning environments including lectures, recitations, labs and homework. A total of 10 sets of problem materials were used for each group: 5 sets in lecture, 3 in recitation, 1 in lab and 1 for homework. Each synthesis problem used in the training involved two concepts; one always came from the chapter on rotational motion and angular momentum that was being taught, and the other concept was widely distributed throughout the other mechanics chapters studied during the quarter. It is important to note that the conservation law of linear momentum was not addressed in the training. Despite the different tasks for each group, time on task was managed to be closely equivalent for all groups except that we had no control over how much time students spent on homework.

A common final examination, which was cumulative, ensued 4 days after the training. The synthesis problem shown in Fig.2 was included to evaluate student performance after the training. This is a challenging problem as reported in our previous work [9]; it describes a situation where a bullet penetrates a wood block fixed at the edge of a free-to-move disk resting on a frictionless surface. To determine the motion of the disk after collision, one need apply the conservation laws of both linear and angular momenta, two topics that are introduced respectively in the early and late stages of a mechanics course. All students, regardless of their group, were required to directly solve this problem without receiving any guidance. Here, we were particularly interested to see how the SSG students performed in this case in which scaffolding was removed.

Students' written responses were collected, photocopied and then blind-coded to ensure researchers analyzing solutions were not influenced by students' group information. Two of the authors (LD and NWR) independently analyzed students' written work using the following grading rubrics.

(1) Identification: Did the student correctly identify the motion of the disk (linear and rotational motion)?

(2) Consideration: Did the student provide any written evidence showing that he/she considered using pertinent fundamental principles as a start (the linear and angular momentum conservation laws)?

(3) Expansion: Did the student make any proper expansion of these principles? (To meet this criterion, the student must clearly list the bullet-disk system's initial and final linear/angular momenta, and equate them to solve for the disc's final linear/angular speed.)

The two researchers agreed on 96% of all instances; the remaining divergence was resolved after discussion.

Tom shoots a bullet of mass m = 0.02 kg and initial velocity v = 300 m/s at a wood block attached to the outer rim of a disk, which in turn rests on a horizontal frictionless air table. The bullet rips through the block, emerging in the same direction, but at a lower speed of 100 m/s. Tom sees that the mass of the wood block can be ignored, so that the disk has a moment of inertia , with M = 1 kg and R = 25 cm. (a) In what direction does the disk move after the collision? (b) What is the total kinetic energy of the disk after the collision?

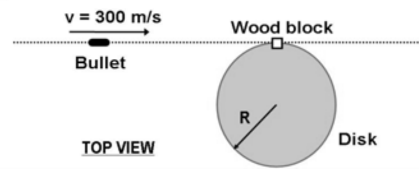


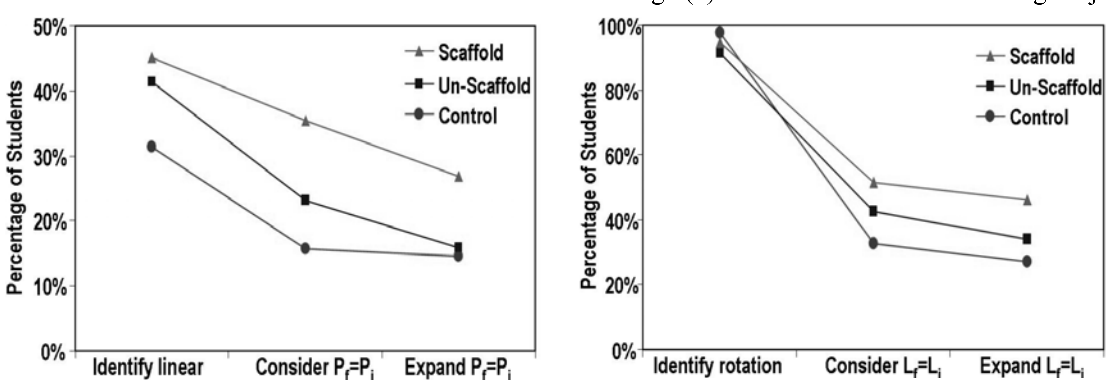
Figure 2 A synthesis problem on the final exam. All students directly solved this problem without scaffolding.

RESULTS

Since this problem involved both topics that were covered (the angular momentum conservation law) and not covered (the linear momentum conservation law) in the training, we examined student performance on each topic individually. Fig.3 shows the results on the success rate in each step—*identification*, *consideration* and *expansion*—for all groups.

For the linear momentum topic, Fig.3(a) shows that the SSG students outperformed the other two groups in all aspects: *identification*, *consideration*, and *expansion*. Take the CG as a baseline; the SSG students demonstrated a statistically better performance in both considering [$\chi^2(1)=9.26$, $p=0.002$] and expanding [$\chi^2(1)=4.15$, $p=0.04$] the linear momentum conservation law, and a marginally better performance in correctly identifying the disc's linear motion [$\chi^2(1)=3.61$, $p=0.06$] [10]. On the other hand, the USG students only achieved a success rate comparable to that of the CG in these three aspects [identification: $\chi^2(1)=1.85$, $p=0.17$; consideration: $\chi^2(1)=1.52$, $p=0.22$; expansion: $\chi^2(1)=0.05$, $p=0.82$].

Fig.3(b) shows that an overwhelming majority of



(a) **(b)**

Figure 3 Student performance on a final exam synthesis problem: (a) performance on linear momentum topic; (b) performance on angular momentum principle.

the students in all groups correctly identified the rotational motion of the disc, a result likely due to a "recency effect" [11], since this topic was the focus of the training and teaching in the last two weeks. This fact notwithstanding, student performance of each group diverged for the "*consideration*" and "*expansion*" of the angular momentum conservation law. The SSG students again demonstrated a highest success rate in both of the subsequent steps, and their better performance in comparison with that of the CG was statistically significant [consideration: $\chi^2(1)=6.75$, $p=0.009$; expansion: $\chi^2(1)=7.26$, $p=0.007$]. However, the USG students only achieved a success of an intermediate level, and their performance was comparable to that of the CG [consideration: $\chi^2(1)=1.86$, $p=0.17$; expansion: $\chi^2(1)=1.04$, $p=0.31$].

The above results indicate that students (SSG) who were trained with the full treatment (scaffolded synthesis problems) demonstrated the highest performance in recognizing and applying relevant physical concepts on a challenging synthesis problem even *after* the scaffolding was removed. Perhaps more importantly, these students outperformed the other groups on topics that were both covered and not covered in the training, signaling their capability of making a cross-topic transfer in solving this problem.

It is worth noting that the above comparison results were derived from using our grading rubrics that purposefully concentrated specifically on students' approach. If our comparison were based on teaching assistants' grading (SSG average: 13 out of a total of 20 points, USG: 12 and CG: 11), which focused mostly on students' final answers, difference between the SSG and the baseline CG would only be significant at the $\alpha=0.11$ level ($p=0.11$), and the difference between the USG and CG would still be insignificant ($p=0.60$). This suggests that although more SSG students could correctly identify and apply the pertinent fundamental concepts, they still had difficulty in combining the two concepts to obtain a final correct answer.

CONCLUSIONS AND DISCUSSION

This study is part of our continuing effort to investigate how the use of conceptually scaffolded synthesis problems may enhance student problem solving abilities. Our goal is to induce students to rely on fundamental concepts for solving physics problems, an approach regularly employed by experts. To that end, we designed synthesis problems combining concepts that are broadly separated in the teaching timeline, and used them as a remedy for formula-based approach, which is most useful for solving traditional end-of-chapter exercises. To further encourage students to look for underlying concepts, we encapsulated each synthesis problem into a sequence with two preceding conceptually-based questions that share with it the same underlying structure. These questions, together with an explicit reminder to look for the underlying connections, were used as guided conceptual scaffolding.

This study was specifically designed to examine the sustained effects of using scaffolded synthesis problems among students. Our results show that repeated training with scaffolded synthesis problems helped students to identify and utilize relevant physical concepts when solving problems even *after* the scaffolding was removed. Moreover, students who received this training exhibited the highest success on making a cross-topic transfer by outperforming their peers on both concepts that were covered and not covered in the training. However, it should be noted that while this method has improved a student's ability to identify and utilize physical concepts in a problem, it has not produced significant improvements in the ability of students to obtain a correct final answer. More research is required to determine where the process is breaking down. Since there is evidence that the students recognized the individual concepts, the breakdown may be at the level of combining the concepts in a consistent manner.

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