

Using Conceptual Scaffolding to Foster Effective Problem Solving

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Abstract. Traditional end-of-chapter problems often are localized, requiring formulas only within a single chapter. Students frequently can solve these problems by performing “plug-and-chug” without recognizing underlying concepts. We designed open-ended problems that require a synthesis of concepts that are broadly separated in the teaching time line, militating against students’ blindly invoking locally introduced formulas. Each problem was encapsulated into a sequence with two preceding conceptually-based multiple-choice questions. These conceptual questions address the same underlying concepts as the subsequent problem, providing students with guided conceptual scaffolding. When solving the problem, students were explicitly advised to search for underlying connections based on the conceptual questions. Both small-scale interviews and a large-scale written test were conducted to investigate the effects of guided conceptual scaffolding on student problem solving. Specifically, student performance on the open-ended problems was compared between those who received scaffolding and those who did not. A further analysis of whether the conceptual scaffolding was equivalent to mere cueing also was conducted.

Keywords: Conceptual scaffolding, problem solving, cueing.

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INTRODUCTION

Problem solving has long been a focus of physics education research. [1]-[8] Studies on expert-novice differences show that experts search for underlying concepts before solving a problem whereas students begin by looking for formulas without understanding its “deep” structure. [9],[10] Since routine end-of-chapter problems (EOCs) often address only concepts covered in one single chapter, students usually can get a correct answer by doing “plug-and-chug” with locally introduced formulas. In a sense, students are rewarded for adopting a novice-like problem-solving approach. Something beyond EOCs is needed to move students toward a more expert-like approach. Using grading rubrics to highlight conceptual knowledge in problem solving has been reported to be successful. [11],[12] A recent study also shows that using isomorphic question pairs (a quantitative question preceding a qualitative question) can help students discern the between-question similarities and hence improve their performance on the qualitative question (but not on the quantitative question, though students can go back and forth to change their answers). [13]

Building on these studies, we propose to use problems containing multiple concepts that are separated in the teaching time line to foster effective

problem solving among introductory-level students. We hypothesize that repeatedly solving such problems, along with guided scaffolding, may encourage students to increasingly search for underlying concepts. As an initial effort, we designed several such problems. Each problem is encapsulated into a sequence with two preceding multiple-choice questions that share the same underlying concepts. An example sequence is given in Fig.1. The goal is to use conceptual questions as guided scaffolding, providing students with qualitative preparation and encouraging them to always search for fundamental concepts.

We conducted pilot studies using both small-scale interviews and a large scale written test to investigate the effect of this guided conceptual scaffolding. Specifically, we sought to answer the following two research questions: (1) *How do students receiving conceptual scaffolding perform on the open-ended problems compared to those who do not?* (2) *What difference does it make if students are provided with conceptual scaffolding instead of cueing?* In this case, “cueing” means explicitly telling students what concepts are involved in solving the problem.

RESEARCH DESIGN

1. Small Scale Interviews

Small-scale interviews were conducted to compare how students perform on the open-ended problem in Fig.1 both with and without conceptual scaffolding. We recruited 12 students from a 3rd quarter calculus-based introductory physics course for one-on-one private interviews. (This course covered topics on waves, optics and modern physics.) The students were randomly assigned into two groups: a scaffolding group (SG) and a plain-problem group (PPG), with 6 each. During the interviews, students were asked to talk aloud while performing required tasks. The PPG students were only given the open-ended problem in Fig.1 without answering the preceding conceptual questions, whereas the SG students answered the conceptual questions in Fig.1 before solving the problem. The SG students were also reminded to look

for underlying connections before solving the open-ended problem, but no explicit assistance was given. Students in both groups were allowed to use their textbooks, notebooks and calculators. All interviews were video taped and later transcribed for analysis.

Results show that all six SG students were able to invoke the correct physics principle (the work-energy theorem) to tackle the open-ended problem without referring to textbooks or notes. Though some students obtained incorrect numerical answers due to calculation errors, all of them provided appropriate qualitative analysis and reasoning. Specifically, these students correctly identified the system's initial and final mechanical energy, and realized that the reduced final mechanical energy resulted from the work done by friction. For instance, one student articulated: "We don't know whether or not this [$x=0.6\text{m}$] is when the spring is at its maximum compression... But we can use the ideas from last two questions that mechanical energy may not be conserved, but we can figure out what the work is done by friction. And because of that, then we can figure out what change in kinetic energy is at any point..." This was a typical case among the SG students. In fact, all SG students immediately recognized the underlying connections between the open-ended problem and the conceptual questions. The average time the SG students took to realize such connections was 33 seconds. Based on the work-energy theorem, all SG students then used a "forward" [14] solution strategy, working top-down from the basic theorem to the final answer. In a post-interviewer debriefing, all SG students strongly favored using this type of question sequences in recitations and lectures.

Conversely, none of the PPG students was able to solve the problem. However, when asked to determine the speed of a harmonic oscillator at some intermediate point in the absence of friction, all of the PPG students took a correct approach. It was the combination of oscillatory motion and friction (concepts broadly separated in presentation) that gave students difficulty. These students often adopted novice problem-solving strategies to approach the problem. For example, after reading the problem some students immediately began thumbing through their notebooks to search for equations that involve "damped oscillation". But soon they found themselves deeply buried into the assorted symbols of a differential equation and become increasingly confused with the math impasse. Other students spent considerable time trying to find similar worked-out examples in the textbook. Some students explicitly commented that they would do a random search to "just start charting down everything that was relevant and see if anything came out of it. But it'd be just a short in the dark." Since these students couldn't relate the given information to the unknowns, they always

A small object attached to a spring of stiffness k is oscillating on a smooth surface, where the frictional force between the object and the surface is negligible. Initially the mechanical energy of the spring-object system is E_i . After the block travels a distance of d , how does the total mechanical energy of the spring-object system change?



- (1) It remains the same: E_i
- (2) It increases by a value of kd^2
- (3) It increases, but the increased value is unknown
- (4) It decreases by a value of kd^2
- (5) It decreases, but the decreased value is unknown

(a)

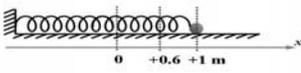
A small object attached to a spring is oscillating on a rough surface, where the frictional force between the object and the surface is a constant f . Initially the mechanical energy of the spring-object system is E_i . After the block travels a distance of d , how does the total mechanical energy of the spring-object system change?



- (1) It remains the same: E_i
- (2) It increases by a value of fd
- (3) It increases, but the increased value is unknown
- (4) It decreases by a value of fd
- (5) It decreases, but the decreased value is unknown

(b)

A small ball of mass 0.05 kg is attached to a spring of stiffness 2 N/m , and it oscillates along the x axis on a rough surface. Initially the maximum spring stretch is 1 m . Due to the friction between the ball and the table surface, the maximum stretch of the spring gets smaller. After traveling a distance of 3.8 m , the ball is at the position $x = +0.6\text{ m}$. At this moment what is the speed of the ball? The frictional coefficient between the ball and the table surface is $\mu_{\text{kinetic}} = \mu_{\text{static}} = 0.2$.



(c)

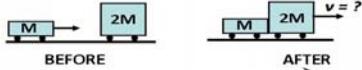
Figure 1. A sequence example: (a) and (b) are two conceptually-based multiple-choice questions; (c) is an open-ended problem that synthesizes broadly-separated topics in teaching materials.

ended up using “means-ends” [14] analysis to approach the problem. Specifically, they started with a formula that contained the speed variable and tried to solve it. Then they looked for additional formulas if the first one contained other unknowns. This process continued until no further unknowns were introduced. One interesting observation is that although the PPG students were only given one problem to solve, they spent about the same amount of time on the problem as the SG students on the same problem plus two conceptual questions (~20 minutes).

2. Large Scale Written Test

A large-scale written test also was conducted with students in an introductory mechanics course. The conceptual questions and the open-ended problem we used for the written test are shown in Fig.2. The

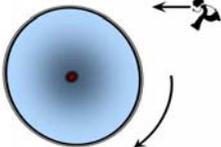
On a frictionless surface, a car of mass M is moving at a speed of 10 m/s toward another stationary car of mass $2M$. Subsequently, they collide and stick together. What is the final speed of the two car system?



- 0 m/s
- 3.3 m/s
- 5 m/s
- 6.6 m/s
- 10 m/s
- None of the above

(a)

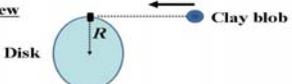
A merry-go-round is initially spinning clock-wise around its axial with negligible friction. A child is running at a certain speed towards the merry-go-round, jumps on and stays near its edge. Consider the child and the merry-go-round as a system. How does the angular momentum of the system change after the child jumps on the merry-go-round?



- Increases
- Decreases
- Remains the same
- Cannot be determined

(b)

Tom throws a clay blob of mass m at a massless “black clay catcher” located on the outer rim of a puck which in turn is riding on a horizontal frictionless air table. The clay is moving at a speed of v in a direction tangent to the rim of the puck just before it sticks onto the catcher. Initially stationary, the system of puck plus clay after impact begins moving on the frictionless surface. Tom sees that the metal puck is a uniform disk with a mass of M and a radius of R . Remember all uniform disks have a moment of inertia $\frac{1}{2} MR^2$. What is the final total energy of the moving puck plus clay system?



(c)

Figure 2. A sequence used for a large scale written test. (a) & (b) are conceptual questions; (c) is an open-ended problem.

purpose of this written test is twofold. First, we wanted to see if the results from small-scale interviews could be generalized to a larger sample. Secondly, it was suggested that our conceptual scaffolding might be equivalent to simple cueing [15]. If that were the case, then the preceding conceptual questions might not be necessary.

The written test was given to 360 students in 16 parallel recitation sections. These were randomly divided into three groups: scaffolding group (SG), plain-problem group (PPG) and cueing group (CG), with 143, 109 and 108 students in each. The SG students were directed first to answer two conceptual questions, and were allowed 5 minutes to do so either individually or collaboratively. Then, each student independently solved the subsequent problem in 12 minutes. Prior to solving the problem, the SG students again were encouraged to look for underlying connections. The PPG students were given 17 minutes to solve the open-ended problem without answering the preceding conceptual questions. The CG students also did not answer the preceding conceptual questions; but before they solved the problem a hint: “*Momentum and angular momentum may play a role*” was given on their test sheets. The allotted time for the CG also was 17 minutes. Students in all three groups were allowed to use their notes and textbooks.

We were more interested in how students approached the problem than whether they obtained the correct final answer. (Actually, the problem is complicated by the fact that after collision the center-of-mass of the disk-blob system is no longer at the disk center. In the future we plan to use a projectile that exits the catcher at a slower speed so that the disk will still rotate about its center after collision.) We examined students’ written responses to see if they considered two fundamental principles appropriate for this problem: the conservation of linear momentum and angular momentum. We also evaluated whether students made meaningful use of these two fundamental principles. The following rubrics were applied:

1. *Consider Fundamental Principles:* Did students show written evidence of considering linear or angular momentum, or stating that linear or angular momentum is conserved?

2. *Meaningful Expansion:* Did students make a meaningful expansion of the fundamental principles to determine the final linear or angular speed of the system? (For example, writing down the initial and final angular momenta, and equating them to solve for the final angular speed.)

Fig.3 shows the percentages of students who considered and made meaningful expansions of the fundamental principles in each group. A higher percentage of students in the SG and CG started with

the fundamental concepts than in the PPG. But the percentage was comparable between the SG and CG [$t(249) = 0.67, p = 0.50$]. This result suggests that simple cueing can be equally effective in prompting students to consider fundamental concepts. However, Fig.3 also shows that a larger fraction of students in the SG *made a meaningful use* of the fundamental principles than in the CG and the PPR [CG: $t(249) = 3.19, p = 0.0016$; PPG: $t(250) = 2.54, p = 0.0118$]. This indicates that cueing is not as effective as conceptual scaffolding in helping students to make sensible applications of the cued concepts.

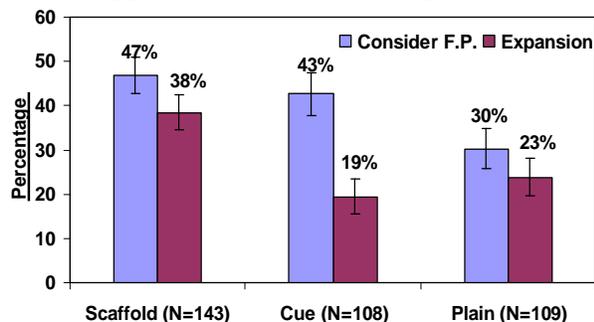


Figure 3. The percentages of students that considered and made a meaningful use of the fundamental concepts. (Error bars are standard errors.)

CONCLUSION AND DISCUSSION

Using conceptual questions as guided scaffolding shows potential for encouraging reliance on conceptual knowledge in problem solving. Students who answered preceding conceptual questions were more able to recognize the underlying connections than those who did not. Likely, the conceptual questions have prepared students with basic concepts needed for subsequent problem solving, hence triggering students to attend to the deep structure of the problem.

Using conceptual questions as guided scaffolding also is beyond mere cueing. Students who received cueing could be prompted to recall relevant concepts, but they were less able to perform meaningful applications of these concepts than students who answered our conceptual questions.

These pilot results have important implications for our future work. If students experience repeated exposure to such practices, they may begin to approach problem solving by searching for underlying concepts. However, it is crucial that students realize a blind use of “plug-and-chug” is fruitless. To achieve this, problems must be designed in such a way that they cannot be solved by invoking locally introduced formulas. Since our ultimate goal is to train students to be independent competent problem solvers, we also plan to investigate optimal ways of gradually

removing scaffolding while still sustaining its effects in promoting effective problem solving among introductory-level students.

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