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Translating Education Research Into Practice Within an Engineering Education Center: Two Examples Related to Problem Solving*

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This paper describes how results from the education literature have been put into practice in two projects currently underway in an engineering education center. The projects are both aimed at improving problem solving. The first is being conducted in Statics, and the second in Fluid Mechanics course in Civil Engineering. The Statics project is grounded in a model that integrates literature on problem solving, representational transformations, and prior knowledge. This model was used to analyze students' problem solving in Statics so that key difficulties could be identified. Instructional modules were then designed to address those difficulties. The design of these instructional modules served as the starting point for modules in Fluid Mechanics. The primary literature used in the development of the instructional modules focused on cognitive modeling, self-explanation, and worked examples.

Keywords: problem solving; self explanation; cognitive modeling; worked examples

1. INTRODUCTION

LIKE MANY engineering education centers, the Leonhard Center for the Enhancement of Engineering Education at Penn State has multiple missions including assisting with assessment and providing faculty development workshops. Its main mission, however, is to enable enhancements in pedagogy, courses, and curricula. To execute this mission, the Center supports projects with individual faculty members and with faculty teams. The staff of the Center, who have expertise in engineering education, educational psychology, and instructional design, strive to translate relevant education research into practice as they execute projects funded by the Center. In addition, Center projects often involve collaborations with colleagues from the College of Education that facilitate translation of education research into practice

In this paper, we will describe how results from the education and engineering education literature have been put into practice in two projects currently underway. The two projects are aimed at enhancing problem-solving in Statics and utilizing instructor-generated videos to enhance problem-solving in Fluid Mechanics in Civil Engineering. The Statics project, funded by the National Science Foundation, is in its third year, so substantial progress has been made and reported, e.g., see [1]. Some of the results will be summarized in this paper as evidence of the effectiveness of the approach.

In parallel to the Statics project, the Leonhard Center started an initiative to put Tablet PCs into the hands of engineering faculty members [2]. After two rounds of distributing Tablet PCs and assisting instructors in using them in the classroom, we shifted our focus to projects that allowed us to investigate more novel ways of using the Tablet PCs to improve learning. One of the projects that we are supporting is the development of an instructional framework for using instructor-generated videos to improve students' ability to solve problems in Fluid Mechanics. The Fluid Mechanics project builds directly on, and extends, our work in Statics, drawing upon additional literature. This project is in the initial stages so no results are yet available. We discuss it to show how additional research findings are being incorporated into practice.

2. ENHANCING PROBLEM-SOLVING IN STATICS

2.1 Background and motivation

Our project to enhance problem solving in Statics was the result of the convergence of two sets of discussions. The first was with Engineering Mechanics instructors about the difficulties that students have in creating and using free-body diagrams in introductory Mechanics courses. The second was a conversation by the lead-author with colleagues in Educational Psychology about potential research collaborations, which included

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studies of the problem solving process. These discussions led to the development of a research project with two goals: to identify the most significant difficulties that students encounter in creating and using free-body diagrams and to develop instructional modules to remediate them.

The first phase of the work involved the use of cluster analysis and think-aloud methods, and the second phase involved a series of 'design experiments' to develop the instructional module. We chose to focus the work on Statics because it is the first course in the introductory Mechanics sequence, and it has a large enrollment, ~600 students per year, making it ideal for large scale studies.

The problem solving process in Statics typically begins with a fairly well defined problem consisting of a short problem statement, often with an associated figure. As students read the problem and study the figure, they begin to form a mental model of the problem. They are generally instructed to create a free-body diagram that contains the elements of the problem that are critical to the solution. From the free-body diagram, they must construct the set of equations required to solve the problem.

2.2 Phase 1: Identifying difficulties during problem-solving

2.2.1 Related educational research

As they proceed from the problem statement to the solution, students engage a problem solving process, either one of their own or one specified by the instructor. In order to solve the problem, students must draw on pertinent prior knowledge, e.g., the nature of reactions that may be present at a specific contact between the body and its surroundings. They must also must work across multiple representations of the problem as their solution unfolds, i.e., the problem statement, the engineering diagram, and the set of equations. Thus, three areas of the literature informed the first phase of our work in which we studied the students' performance in the think-aloud sessions: problem solving, representational transformations, and prior knowledge.

Polya, who studied how students solve mathematics problems, established the utility of having novices learn and use a well-defined sequence of steps during problem solving [3]. Many models for problem solving can be found within the engineering education literature. Woods, [4] for example, advocates a six-step model for complex problem solving, and Gray *et al.* [5] suggest a five step model. Other researchers frame problem solving in terms of the cognitive processes that are engaged. Mayer and Wittrock identify the cognitive processes involved in problem solving as: representing, planning/monitoring, executing, and self-regulating [6]. In our work, we used a four step model that blends the cognitive processes with a model similar to that of Polya: (1) Represent the Problem, (2) Set Goals and Plan Solution, (3) Execute the Plan, and (4) Evaluate the Solution.

In the first step, problem representation, the student reads the problem statement and attempts to discern the objective. Correct execution of this step is heavily dependent upon the student's ability to determine the deep structure of the problem and recognize the principles that must be applied to reach a solution. In engineering, this step will typically include creation of an engineering representation of the problem. Although all steps in the problem solving process are important, the need to accurately represent the problem may be particularly critical [7]. Research in this area has shown that individual differences in how students represent problems are tied to differences in problem solving performance. Sherin, for example, demonstrated that college students who struggle to understand a physical situation also have difficulty expressing that idea as a mathematics equation [8]. Savelsbergh *et al.* divided physics students into groups of strong and weak novices. They found that these two groups could be differentiated by their ability to represent problems [9]. This literature led us to focus strongly on the creation of the free-body diagrams in our work.

A second area of the literature that we used focuses on the symbol system translations inherent in the problem solving process. By symbol system, we refer to the semiotic system used to understand and express elements and their relations. Mathematical expressions are an example of a semiotic system in which numbers and operators act as elements. How these elements are configured in relation to one another communicates the full meaning of the expression. Translations are required when problem solvers move between symbol systems. In solving a Statics problem, students must translate among the problem statement, which is usually text and a figure, a free-body diagram, and the set of equilibrium equations.

McCracken and Newstetter [10] developed a model to capture the translations that take place during problem solving. Their model includes verbal (Text), visual (Diagram), and mathematical (Symbol) semiotic systems. In this model, the student must pass through three phases to complete an analysis task. Each phase corresponds to a different symbol system. Accurate problem solving relies on the ability to move through the phases by transforming a representation of the problem from one symbol system to another. In order, the problem solver must move from the verbal representation, through the diagram, and onto a mathematical expression. McCracken and Newstetter argue that, although these representational systems are tightly bound in the expert, novices must work harder to pass from one phase to the next. Their assertion is consistent with a broader literature that addresses the degree to which students integrate, or map between, different representational systems during learning and problem solving. On balance, this research shows that college students often struggle with the task of integrating information across symbol systems [11].

The final area of the literature that we drew upon for the first phase of the Statics project involved the effects of prior knowledge on problem solving. It is well established that the quantity of prior knowledge affects the ability to solve problems [12]. The impact of inaccurate prior knowledge and misconceptions is also well represented in the literature. When learners' prior knowledge contains inaccurate conceptions, these underlying errors are passed on to the mental model that is constructed to solve a problem. When the faulty knowledge plays a central role in the solution for that problem, the error in the underlying structure is passed on as an error in the outcome performance. Thus it was important to consider the role of domain knowledge as we observed students solving problems.

The literature from these three areas was combined into an integrated model of problem solving, presented in Table 1 [13]. The model has three phases, following the work of McCracken and Newstetter: Recognition, Framing, and Synthesis. Within each phase, three processes are considered: problem solving, use of prior knowledge, and interpretation of the associated symbol systems. Iteration among the phases and interaction across the processes within a phase are expected. This model guided the analysis of student performance during the think-aloud sessions described in the next section.

2.2.2 Summary of Methods and Results

Overall this portion of the project required nearly two years. It began with collection of data from hundreds of students on three inventories: a math baseline test, the Statics Concept Inventory, and two spatial reasoning measures. This data was used to perform a cluster analysis to identify groups of students with similar knowledge and skills. Students from each of the clusters were then invited to participate in think-aloud problem solving sessions in order to identify the major difficulties that they were experiencing in solving Statics problems. During these sessions, students were asked to think-aloud while they created a free-body diagram and a set of equilibrium equations for three typical problems.

A team of engineering experts scored the written work from the think-aloud sessions to determine the areas of technical weakness of the students. The educational psychology researchers on the team reviewed the problem solving processes of the students and coded them based on the Integrated Problem Solving model. Details of the data collection and analysis are described in References 14 and 15.

The major observations from the analysis of the videos and written work were that failure to create accurate and complete free-body diagrams was most often associated with inadequate domain knowledge, especially an inability to reason through the reactions that could be present at a given interaction of the body and its surroundings. For most students, neither basic problem solving processes nor transformations among the various symbol systems were found to be a major barrier. Thus our work pointed to domain knowledge as one of the keys to successful problem solving in Statics.

Based on this observation, we compared use of domain knowledge by successful and unsuccessful students. Distinct differences were found in how these two groups of students applied their knowledge during problem solving. The stronger problem solvers used their knowledge to anticipate what steps should happen next and also to identify which principles might apply to the problem. These differences are quite consistent with the literature on the role of self-explanation in problem solving that will be discussed below.

2.3 Phase 2: Creation and testing of instructional module

2.3.1 Related educational research

Given this striking difference in the use of self-explanation and the strong literature basis supporting the importance of self-explanation in successful problem solving, we decided to incorporate self-explanation into our instructional module. The module was built based on two main results from the literature: the efficacy of cognitive modeling in teaching problem solving, and the role of self-explanation in developing domain knowledge and problem solving skills.

Table 1. Integrated problem solving model

	Problem-solving processes	Prior knowledge	Symbol systems
Recognition	Understand the problem, set goals, plan.	Pattern recognition, Identification of deep structure.	Primarily verbal, but also visual.
Framing	Execute plans, map givens and knowns, monitor, evaluate diagram.	Applying concepts (e.g., force, couple, moment, etc.). Applying procedures (e.g., drawing force vectors, adding dimensions, etc.).	Primarily diagrammatic.
Synthesis	Execute plans, monitor, evaluate solution.	Governing equations, algebra, trigonometry.	Primarily algebraic.

Mayer describes cognitive modeling related to problem solving as 'having a competent problem solver describe her thinking process as she solves a real problem in an academic setting' [16]. He also states that cognitive modeling is 'the most successful instructional strategy for teaching students to control their own mathematical problem-solving strategies.' Collins, Brown, and Newman discuss such modeling and its potential to enhance both cognitive and metacognitive skills in their work on 'cognitive apprenticeships' [17]. Because of the effectiveness of cognitive modeling, our module begins with the instructor working through an example in detail. As she works the example problem, the instructor explicitly demonstrates the type of reasoning that she is seeking. Therefore she is modeling the cognitive behavior that she wants her students to use.

A very substantial literature exists on the efficacy of self-explanation. Chi and co-workers conducted a study of how students use examples as they learn to solve problems [18]. In a summary of the self-explanation research, Roy and Chi [19] observe that self-explanation is an effective constructivist activity that is a significant predictor of a learner's ability to build deep understanding. Roy and Chi also point out that learners vary substantially in the extent to which they engage in self-explanation without prompting. They go on to point out, however, that a number of studies have demonstrated that prompts can be used to generate more self-explanation and that the prompted self-explanation leads to enhanced performance.

The effectiveness of self-explanation led to the inclusion of prompts to generate self-explanation in our module. To encourage students to do high quality self-explanations, the instructor emphasizes the importance of self-explanation in learning as part of her video. After watching and listening to the instructor work an example problem, the students begin to solve a series of similar problems. In all of these problems, students are prompted to enter an explanation for their answers. After students complete each problem, they are given access to a video that discusses and provides additional modeling of the desired reasoning process to further reinforce the use of domain knowledge that is desired.

2.3.2 Summary of methods and results

The instructional module was developed using an iterative process in which it was tested, refined to enhance effectiveness, and then re-tested [15]. The initial testing occurred with small groups of students completing paper-and-pencil versions of the module. In this testing an engineering instructor answered their questions and discussed the correct solutions. Two additional rounds of testing occurred. In each round, less interaction with the instructor occurred because the goal of the development process was an instructional module that would standalone.

In addition to the instructional module, a ten-question assessment instrument was developed to determine the effectiveness of the module. Eight of the ten items focused on specific connections and asked students to choose the correct free-body diagram for the connection and to select statements that justified their choice. The other two items asked students to select the correct free-body diagram of complete bodies.

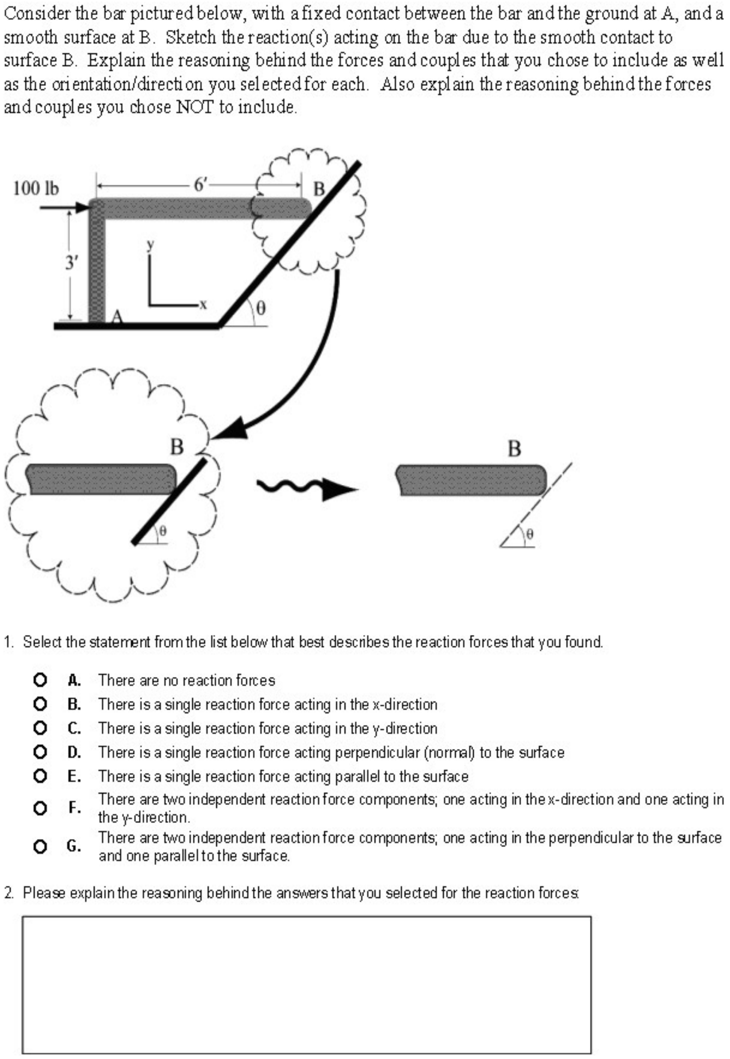
The instructional module was implemented within a course management system. It requires students to engage in self-explanation as they solve problems. Figure 1 is a screen shot of a portion of one of the problems that students were asked to solve; note the prompt for self-explanation above the textbox. In this case, they were to select the figure that showed the reactions that could be present and then type in the justification for their selection. The students did five problems of this type. They also solved five problems that required them to identify errors in free-body diagrams and to justify their answers. After each problem, students can view a solution video that reinforces the type of reasoning that is desired by the instructor.

A pretest/posttest evaluation of the effectiveness of the instructional module was conducted using the instrument developed during the design experiments. In assessing the effectiveness of the module, we used a Solomon Four-group [20] experimental design involving 220 students who were taking Statics. The results of the study showed that the instructional module led to substantial, statistically significant improvements in performance [1]. Figure 2 presents the average scores for 55 students who completed the pretest, the instructional module, and the post-test. The average accuracy of selection of the free-body diagrams and the accuracy of the choices of justification statements increased by 0.6 standard deviations from the pretest to the posttest. In addition, the number of incorrect justifications selected decreased by the same amount. Thus, the results of the study provide evidence that the combination of cognitive modeling and prompting self-explanation by the students is effective in improving their ability to identify correct free-body diagrams and to select correct reasoning to support their selection.

3. EXTENSION OF APPROACH IN FLUID MECHANICS COURSE

3.1 Background and motivation

We are in the early stages of a new project to extend the approach developed in Statics. This work is being done in the introductory Fluid Mechanics class in Civil Engineering and takes advantage of the ease with which instructors can generate narrated problem solutions using a Tablet PC. The module includes cognitive modeling by the instructor and prompts for self-explanation, similar to the approach used in the Statics work. In



Consider the bar pictured below, with a fixed contact between the bar and the ground at A, and a smooth surface at B. Sketch the reaction(s) acting on the bar due to the smooth contact to surface B. Explain the reasoning behind the forces and couples that you chose to include as well as the orientation/direction you selected for each. Also explain the reasoning behind the forces and couples you chose NOT to include.

1. Select the statement from the list below that best describes the reaction forces that you found.

- ○ **A.** There are no reaction forces
- ○ **B.** There is a single reaction force acting in the x-direction
- ○ **C.** There is a single reaction force acting in the y-direction
- ○ **D.** There is a single reaction force acting perpendicular (normal) to the surface
- ○ **E.** There is a single reaction force acting parallel to the surface
- ○ **F.** There are two independent reaction force components; one acting in the x-direction and one acting in the y-direction.
- ○ **G.** There are two independent reaction force components; one acting in the perpendicular to the surface and one parallel to the surface.

2. Please explain the reasoning behind the answers that you selected for the reaction forces:

Fig. 1. Screen shot from Statics module showing self-explanation prompt.

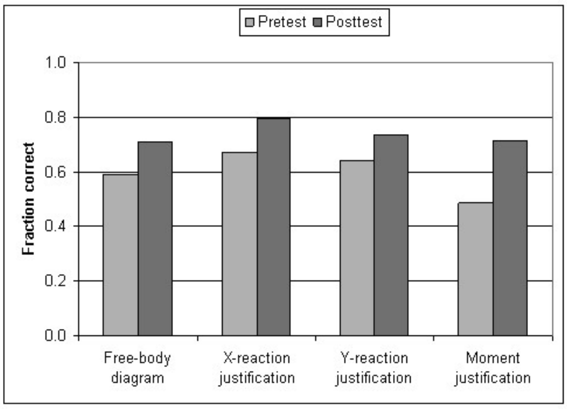


Fig. 2. Average scores for selection of correct free-body diagram and justification statements on pretest and posttest.

addition, it utilizes worked out examples and structured delivery of information to support learning, often referred to as scaffolding in the education literature. In its final form, the module will include the use of 'fading' of the scaffolding as well.

This project was initiated based on a proposal submitted by the instructor of the Fluids course as part of our Tablet PC initiative. He was interested in creating on-line examples to supplement his in-class instruction because available class time did not permit him to do as many examples as he would like. His initial request was for support to create video podcasts of examples. However, he was willing to work with us to create more sophisticated learning materials after he was introduced to the findings of our Statics project.

3.2 Related education research

The core of this instructional module is a worked example created by the instructor using a Tablet PC. Renkl and co-workers have performed a number of studies on the effectiveness of worked examples for novice learners, which are summarized in [21]. Renkl notes that many studies have demonstrated that having students study multiple worked examples prior to starting problem solving is more effective than the 'traditional method' of having students solve problems after seeing a single example. In a paper on how to help students make a transition from studying examples to problem solving, Renkl and Atkinson assert that learning from worked examples is more effective for novice learners than problem solving itself [22].

The theoretical case of these findings is built upon cognitive load theory. Essentially the argument is that novices have so little experience in the domain that they are forced to use generic strategies that are not as efficient as domain specific strategies. Also the domain knowledge of novices is limited and quite likely to be fragmented, compared to that of experts, so that accessing domain knowledge imposes a high cognitive load. Thus, novices experience very high cognitive load when trying to solve problems. The use of worked examples allows them to acquire knowledge with far less cognitive load than problem solving.

The literature on the effectiveness of worked examples led us to use them as the basis of the instructional module that was created for the Fluid Mechanics course. In these worked examples, the instructor makes connections to relevant theory and discusses the rationale for the steps in the problem solving process, i.e., he scaffolds the students' problem solving. Wood *et al.* define scaffolding as 'a process that enables a novice to solve a problem, carry out a task or achieve a goal which would be beyond his unassisted efforts' [23]. The concept of scaffolding evolved from Vygotsky's [24] theory of intellectual development, in which he suggested that intellectual development is not straight-forward, but rather gradual, consisting of series of steps, which are called zones of proximal development. According to this theory, at each step of intellectual development, there are three types of tasks: the tasks that an individual can solve on his/her own (current capacity), the tasks that can be solved with assistance (zone of proximal development), and the tasks that cannot be solved with or without assistance (unattainable). With the help of scaffolding, an individual gradually moves the tasks from the second category to the first one. At the same time, as the level of intellectual development grows, the tasks that previously could not be solved, now can be solved with assistance.

To transition students to problem solving without the scaffolding, it should be gradually withdrawn, a process often referred to as fading. Along with Atkinson and Grosse, Renkl wrote a summary of the work related to the fading of solution steps and the theoretical basis for the effectiveness of the strategy [25]. In his own work, Renkl has done a careful study of details of fading of steps from worked out examples [26]. Among other variables, he compared the effects of fading steps from the end of the solution and from the beginning, i.e., backward and forward fading. He suggests that backward fading may be more favorable from a cognitive load perspective. Because fading has been shown to be effective, we plan to use it in the final version of the modules. We will use item analysis of scores from the pilot tests to identify the items where scaffolding can be removed first.

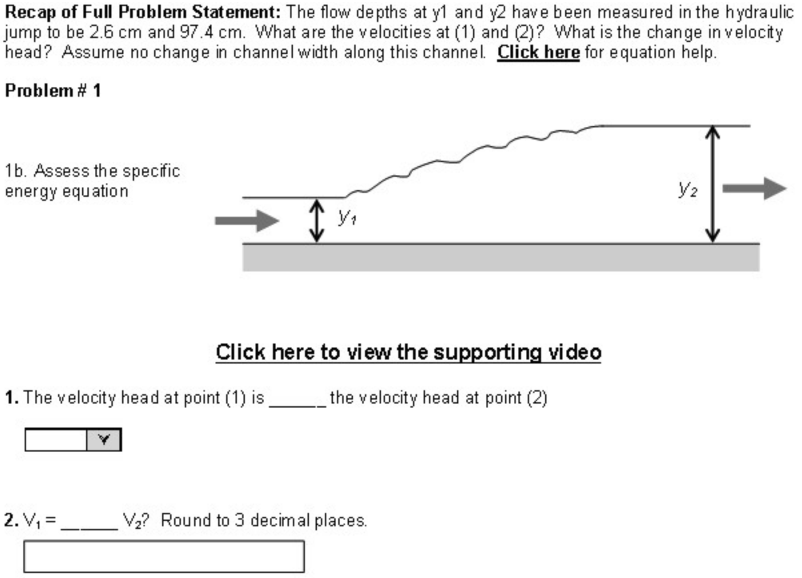
The combination of self-explanation with worked examples has been shown to increase students' ability to apply their knowledge to novel problems that diverge from the set of problems that they have already solved. Renkl *et al.* [27] describe the work that supports this finding. Two groups of students solving probability problems were studied. Both were given worked examples with backward fading. However, only one group received prompts for self-explanation. The prompted group showed better performance in their ability to solve problems similar to the worked examples. They also showed greater ability to use their problem solving skills to solve problems that did not match the worked examples. Based on these results, we have also included self-explanation prompts in this instructional module.

3.3 Implementation and testing

As in the Statics course, the instructional module in Fluid Mechanics was implemented within a course management system. Each module consists of a video-based worked example and a set of three problems. The worked example begins with the instructor's explanation of the topic that includes conceptual information related to the problem, information about the physical phenomena and real-world examples, and an explanation of the equations used for solving the problem. The second part of the video presents the general set-up of the example problem and the demonstration of the steps that are necessary to take to solve the problem. The problems that the students are asked to solve have the same basic structure as the example problem but they increase in complexity.

Each problem in the set of three is divided into sub-problems that ask students to assess the relative relationship among variables and to perform analysis. For example, in solving a problem related to a hydraulic jump the students are asked to assess whether the velocity increases, decreases or remains the same, and then to calculate a velocity ratio (Fig. 3). Other sub-problems include prompts that ask students to explain a calculation or to recall a key principle involved. These prompts are intended to help the students connect the problem solving procedures with the conceptual information and to apply it in the solution of the step. Figure 4 shows a typical screen for this type of sub-problem.

The use of sub-problems allows us to present and scaffold key parts of the analysis using sections of the worked example so that students are not overwhelmed by the demands of the problem solving process. All pages contain a link to key equations if students need that support. After students complete the video problems, they receive an assignment of problems from their text. The students have access to the complete video of the



Recap of Full Problem Statement: The flow depths at y1 and y2 have been measured in the hydraulic jump to be 2.6 cm and 97.4 cm. What are the velocities at (1) and (2)? What is the change in velocity head? Assume no change in channel width along this channel. **Click here** for equation help.

Problem # 1

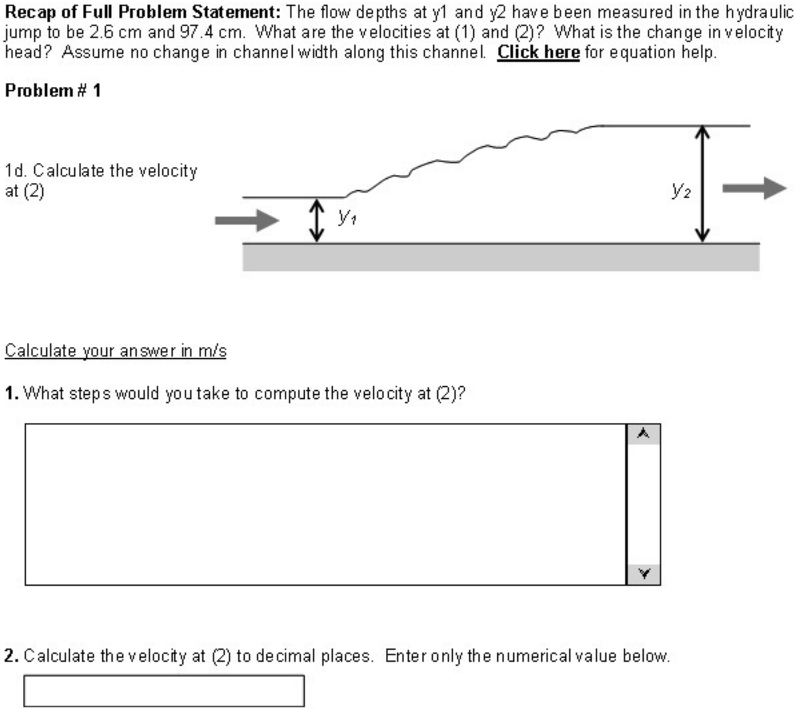
1b. Assess the specific energy equation

Click here to view the supporting video

1. The velocity head at point (1) is ______ the velocity head at point (2)

2. V_1 = ______ V_2? Round to 3 decimal places.

Fig. 3. Sub-problem asking students to a qualitative judgment about the relative size of the velocity head at points 1 and 2 as well as a calculation of the velocity ratio. The section of the worked example video that supports this sub-problem is available via a link.



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Problem # 1

1d. Calculate the velocity at (2)

Calculate your answer in m/s

1. What steps would you take to compute the velocity at (2)?

2. Calculate the velocity at (2) to decimal places. Enter only the numerical value below.

Fig. 4. Sub-problem that includes a prompt to that asks students to explain the steps that they would take to compute the velocity at (2)

worked example after they complete the instructional module. They are free to use it as they do their homework or prepare for the quiz on the topic covered by the module.

We are currently testing instructional modules for two portions of the course: application of the continuity equation to simple systems and application of the specific energy equation along with continuity. The participants of the pilot study are 80 engineering students enrolled in a 300-level Fluid Mechanics course in Civil Engineering. Although the participants have the opportunity to take to complete the module any time during a one-week period, they must complete it in one sitting. To examine the effectiveness of segmented video and self-explanation prompts, participants are exposed to one of the four conditions: (1) segmented video and self-explanation prompts; (2) segmented video; (3) self-explanation prompts; and (4) control. The effectiveness of different elements of the module design will be assessed based on student answers to the sub-problems and scores on a quiz one week after they complete the module.

4. SUMMARY

This paper described how results from the literature were used in two projects to develop instructional modules that would enhance problem solving by engineering students. The primary literature used in the development of the instructional modules focused on problem solving, cognitive modeling, worked examples, and self-explanation. Assessment of the module for Statics demonstrated that it was effective. The module for Fluid Dynamics is just being developed, so its effectiveness is not yet determined. However, given the results of the Statics study and the fact that the module in Fluid Dynamics builds upon it, we have reason to expect it to be successful. One final point worthy of note is how important collaborations between the Colleges of Engineering and Education have been in our process of translating the literature into practice.

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