

Computer Problem-Solving Coaches

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Abstract. Computers might be able to play an important role in physics instruction by coaching students to develop good problem-solving skills. Building on previous research on student problem solving and on designing computer programs to teach cognitive skills, we are developing a prototype computer coach to provide students with guided practice in solving problems. In addition to helping students become better problem solvers, such programs can be useful in studying how students learn to solve problems and how and if problem-solving skills can be transferred from a computer to a pencil-and-paper environment.

INTRODUCTION

The ability to solve problems in a variety of contexts is becoming increasingly important in our rapidly changing technological society. In particular, good problem-solving skills are critically important for scientists and engineers, who use these skills to create new knowledge and to apply existing knowledge to the real world.

Because an introductory course in physics is a prerequisite for study in nearly all science and engineering fields, it is an ideal venue for teaching problem solving. However, studies have shown that the majority of students emerge from such courses having made little progress toward developing good problem-solving skills [1]. One obstacle to students' learning effective problem-solving strategies is the difficulty and expense of providing good coaching, i.e., supplying students with an environment where they receive guidance and feedback while they solve problems. Even when the instructor and textbook model good problem-solving techniques, students often continue to use previously developed weak strategies and not those that are modeled [2].

In this paper, we present a framework for combining previous research in student problem solving with research in student-computer interactions to develop a practical means of providing every student with effective coaching in problem solving. We then describe our ongoing efforts to implement

these ideas by designing a prototype of a computer problem-solving coach for students. Because this type of coaching focuses on the underlying student problem-solving process, it has little in common with existing computer homework systems that provide hints for specific problems. The work described in this paper is concerned with the practicality of building a software coach that interacts with students. After several prototypes have been constructed, we intend to test their efficacy first in small pilot studies of a few students and then in large-scale classroom trials.

RESEARCH BASE

Data exists on curricular interventions designed to help students become better problem solvers [3]. Each of the successful interventions had three common features: (1) explicit teaching of a problem-solving framework, (2) modeling of the use of the framework by the instructor, and (3) students using the framework when solving problems.

All of the problem-solving frameworks are based on the strategy developed by Polya [4]. The Minnesota problem-solving framework, shown in Fig. 1, is a typical example. Since real problem solving is rarely linear, Fig. 1 is meant only to outline the basic stages through which a solver might loop multiple times, and not to imply that problem solving can be reduced to a linear algorithmic process.

Minnesota problem-solving framework

1. Focus the problem
 - Draw a picture illustrating the situation
 - Determine the question to be answered
 - Choose which physics principle(s) to use
2. Describe the physics
 - Draw physics diagrams
 - Determine target quantity(ies)
 - Write down quantitative relationships
3. Plan the solution
 - Select equation containing the target quantity
 - Identify other unknowns in equation
 - Solve a sub-problem to find each unknown
 - Check units
4. Execute the plan
 - Calculate value of target quantity(ies)
5. Evaluate the answer
 - Check if answer is properly stated
 - Check if answer is unreasonable
 - Check if answer is complete

FIGURE 1. The Minnesota problem-solving framework.

In the curricular applications, the instructor models good problem-solving techniques, usually during lectures, making explicit reference to the framework, and students are required to use the framework in their own problem solutions [5]. This strategy for teaching problem solving stems from the cognitive apprenticeship approach [6], in which the instructor models and makes explicit the cognitive processes necessary for performing a task and students are then expected to perform similar tasks with guidance before performing them on their own. In a standard physics class, students may have opportunities to practice solving problems in recitations, where they can receive feedback from both their peers and instructors [7,8].

Built into the framework for successful problem solving are the basic cognitive functions of deciding, implementing, and assessing. At each step in the solution process, the solver must *decide* on an action, *implement* it, and *assess* whether the implementation is adequate. Expert problem solvers perform these functions automatically, as an adult might tie a shoe. Novices, however, must be deliberate in their performance in order to succeed.

Students usually focus on implementing and rarely make deliberate decisions or assess their performance. This failure to make deliberate decisions often results in students' invoking inappropriate or incorrect knowledge, in not recalling useful knowledge they do have, and in applying procedures incorrectly. This process leads not only to incorrect problem solutions,

but also to a failure to learn from one's mistakes. A good problem-solving aid should make these basic cognitive functions explicit to the student and enable the student to practice each one with feedback.

COMPUTER COACHES

One fundamental limitation of the curricular methods described previously is the reliance on interactions with peers or an instructor to achieve targeted coaching. Social interaction is likely a necessary part of an efficient learning process but does not allow for enough guided practice for most students. In many large lecture classes, students have less than one hour each week of organized practice solving problems in the supportive environment of a small group discussion section with a knowledgeable instructor.

The availability of powerful personal computers has led researchers to try to exploit their capabilities to provide students with individualized guidance and feedback [9]. Reif and Scott [10] developed a set of computer coaches called Personal Assistants for Learning (PALs) designed to teach students how to apply Newton's motion law, $\mathbf{F}_{\text{net}} = m\mathbf{a}$. A pilot study of the PALs found that such coaches could help students improve their ability to apply Newton's motion law to solving problems.

Our goal is to build on previous work to develop computer coaches (called PS-PALs or Problem-Solving PALs) that can help students learn to solve the full range of problems they encounter in a typical introductory physics course. PS-PALs differ from PALs in that the previous coaches by Reif and Scott were designed to help students apply Newton's motion law to a problem for which it was already known that such an approach would lead to a successful solution. PS-PALs are designed to coach students in the more difficult and useful problem-solving practice of decision making: it is the student who must decide which physics principle(s) (e.g., kinematics, Newton's laws, conservation of energy or momentum, etc.) are necessary for solving the problem, in addition to applying the principle(s) correctly.

Following the literature on designing effective cognitive tutors [9], PS-PALs are based on a task analysis of the thought processes required to use a systematic problem-solving framework and give students guided practice performing these thought processes while solving problems. PS-PALs also give students immediate feedback on errors and gradually

reduce the amount of help given to students, requiring them to learn to work more independently.

Pedagogy

PS-PALs incorporate all of the previously described characteristics of good problem-solving aids by interacting with the student in three different modes. The first two modes are based on the reciprocal-teaching strategy [11].

In the first mode, the PS-PAL acts as a coach, performing the functions of deciding and assessing, while the student implements. The PS-PAL displays the framework shown in Fig. 1 and graphically highlights each step as it guides the student through solving the problem by breaking the complete solution down into smaller questions. For example, the answers to the first series of questions lead to the construction of a useful picture illustrating the situation, including the relevant objects shown at important time instants and various kinematical and dynamical quantities associated with the objects. The picture aids the student in visualizing the problem situation and also may help to decide which physics principle(s) might be useful in solving the problem. Thus, the PS-PAL *decides* on the step to perform, the student *implements* the step by answering PS-PAL's questions, and the PS-PAL *assesses* the student's answer. If it is wrong, the PS-PAL gives feedback to help the student correct his or her work. A similar method is used to guide students in performing other problem-solving tasks, such as choosing and elaborating the physics principle(s) to use to solve the problem, writing down the quantitative relationships corresponding to the principles, and solving for the desired quantities.

In the second mode of reciprocal teaching, the roles are reversed. The student acts as the coach, *deciding* on the action to be implemented by the PS-PAL. The computer *implements* the action (but may deliberately make a mistake) and the student then *assesses* PS-PAL's implementation and makes any necessary corrections. This mode gives students practice in making deliberate decisions during the problem-solving process and in assessing work. The mistakes the PS-PAL is programmed to make are ones that are commonly found in student solutions.

The advantages of the reciprocal teaching strategy are (1) the instruction is highly interactive so that the student is constantly engaged mentally, (2) the cognitive processes of deciding, implementing, and assessing are made explicit and practiced in the context of solving a problem, (3) the PS-PAL models

both the use of the problem-solving framework and good problem-solving performance for the student, and (4) the student receives individualized guidance and feedback, ensuring effective practice.

The third mode of interaction used by PS-PALs emphasizes the cognitive apprenticeship stage known as fading, slowly withdrawing the scaffolding of the computer program enforced problem-solving framework. The instructional strategy is based on learning from well-studied examples [12]. After students have received guided practice solving some problems as described above, the computer asks the student to solve a similar problem on paper, without any help. It then asks the student a series of questions designed to detect and diagnose any errors. If the student's solution is incorrect, the PS-PAL provides the student with a series of increasingly detailed hints, beginning with a hint to look back at a similar problem that was previously solved with the PS-PAL's guidance (the well-studied example). Students have a chance to correct their solution after each hint and thus receive the minimum amount of help necessary to solve the problem. This fading of assistance is designed to help students develop the ability to work independently.

Guidance and feedback

The guidance and feedback provided by the PS-PALs are primarily process-oriented hints but include some content-oriented hints specific to the particular problem. This is designed to focus students' attention on the use of their own mental framework to solve problems and differs from other web-based homework assistance systems such as WebAssign and Mastering Physics, in which a large fraction of the hints are content-oriented and specific to a particular problem. The intent of this type of coaching is that process-oriented hints emphasize the generality of physics and promote the development of an underlying problem-solving process that helps students transfer their skills to the solving of other problems [9].

Problems

The problems presented by the PS-PALs are "context rich" problems [13]. Such problems (1) are challenging enough that students must use an effective problem-solving framework to reach a solution, (2) require students to make decisions on how to proceed with the solution, (3) have a context and motivation that could help trigger cognitive connections for a student, (4) require students to visualize the situation,

and (5) are mathematically straightforward to solve from basic principles. Traditional textbook problems can often be solved without the use of an expert-like problem-solving framework, so context-rich problems are employed to motivate the use of the framework shown in Fig. 1.

Programming

We use Authorware, a commercial programming language developed by Macromedia as the development language for PS-PALs because (1) Authorware is the product of a large established company that continues to develop and make improvements to the language, (2) Authorware programs can be delivered over the web and run on both Macintosh and Windows computers, (3) Authorware allows for easy incorporation of graphics, sound, and movies, and (4) Authorware is designed to be easily learned by even non-programmers, so that one can focus on instructional design without worrying about programming details. Using Authorware allows for eventual adoption and adaptation of the tutorials by individual instructors. PS-PALs are a test-bed for this type of computer coaching, which probes how much this technology can achieve through good design and the use of effective instructional strategies and without resorting to the complexities of artificial intelligence [14,15] that may be possible in the future.

Assessment

Thus far, we have constructed a PS-PAL prototype for each of the three modes of interaction and are testing them with students both to assess their usability and to gauge students' potential interest in using such computer coaches. All of the students who volunteered to test the programs were enthusiastic about them and said they thought such coaches would help them to become better problem solvers. These students were also able to point out instances where the computer interface was confusing or the feedback provided by the PS-PAL was unclear.

Once we are satisfied that the programs are acceptable to a large fraction of students, our plan is to develop a set of PS-PALs for eight to ten physics problems that can be solved using kinematics, Newton's laws, and/or conservation of energy. We have chosen this set of principles because it represents the point in most introductory physics courses at which problem-solving decisions become challenging for students. Because PS-PALs log all student interactions with the computer, we are able to study

the difficulties students have during the problem-solving process and thus refine the computer coaching structure. We will also test the PS-PALs for educational impact with students in an introductory physics course. The results of that assessment will guide our future work with the PS-PAL computer coaches.

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