A Meta-Cognitive Computer-based Tutor for High-School Algebra

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Abstract: Algebra is an important high-school subject and serves as a gateway to higher math education. Yet many students struggle with Algebra and are left behind. This paper describes a computer-based Algebra tutor for use in tandem with classroom instruction to provide adaptive practice with problem-solving skills. This tutor is designed so as to reify the problem-solving process to the student and bring it to their awareness. This is accomplished in the problem-solving environment that supports each problem with helper sub-problems that are organized in a meta-cognitive framework. The tutor also adapts instruction to provide optimal challenge to each student. In addition, the tutor adapts the interface to provide help suggestions to students who have difficulties solving problems. The tutor is currently being evaluated.

1 Introduction

A good education is extremely important in today's workplace. Studies have shown that there is a widening gap between the rich and poor and that the basis for this divide is the level of education. Unfortunately, the children most in need of a good education, those from poorer families and whose parents are not well-educated, are also most at-risk of not achieving a sound education. It is therefore imperative that special efforts be made to address the particular problems of at-risk children. An extreme solution would be to allocate an experienced, high-quality tutor for each at-risk student. This would certainly provide them the educational experience they need. Obviously, such an approach is prohibitively expensive. A cost-effective compromise is to provide Intelligent Tutoring Systems (ITSs) to each student. ITSs can automatically tailor themselves to the needs of the individual students and approximate the one-on-one educational experience provided by a human tutor. The objective of the Algebra tutor project was to develop and evaluate a fully-functional Intelligent Tutoring System (ITS) for Algebra, incorporating carefully researched instructional strategies and content.

2 Overview of the Solution

We have developed an adaptive tutor to serve as a teaching assistant to Algebra teachers, providing extra remediation and practice in solving Algebra word problems. The Algebra ITS (Intelligent Tutoring System) is designed to be used in tandem with classroom instruction to increase the math proficiency of high school students. The tutor differs from other relatively static computer based training systems by constantly monitoring student performance and tailoring the questions presented to match the skill level of the pupil.

Designing effective instructional strategies was the prime emphasis of this effort. We have based our instructional design on the information we gathered from interviewing several high-school Algebra teachers who have had experience teaching high-school Algebra and through an extensive literature survey of research on effective instructional strategies in general and for Algebra in particular. The following are the key features of our approach: learning-by-doing strategy, incorporation of multiple problem-solving strategies, aids to promote meta-cognitive thinking, schema-based organization of problems, aids to improve reading comprehension, adaptive problem selection, and adaptive help guidance.

At the core of the instructional approach is the "learning-by-doing" approach, where students are taught in the context of solving word-problems. This approach has been strongly recommended in educational literature [Schank, 1995]. The tutor scaffolds the problem-solving task by providing several sub-tasks that break-down the main problem into smaller problems that contribute to the overall solution. Figure 1 shows problem and one of the associated sub-problems. Since research also suggests that it is important for students to be aware of several strategies in order to be effective problem-solvers [Koedinger and Tabachneck, 1994], each problem provides at least one alternate informal strategy in addition to helping students solve the problem algebraically. We have included the following strategies, both of which are commonly used in classroom instruction: 1. Guess-and-check, 2. Pattern-finding.

An important innovation that is unique to the tutor is its meta-cognitive focus with the intent of showing students how to think about problem-solving. The tutor accomplishes this by organizing the sub-problems associated with a word problem into a meta-cognitive framework. This design is based on research that shows that training in meta-cognitive thinking contribute significantly to improved problem-solving performance [Polya 1957, King 1981, Hacker et. al. 1998]. Figure 2 shows the organization of the sub-problems. The questions shown in the network are explicitly represented as navigational hyperlinks.

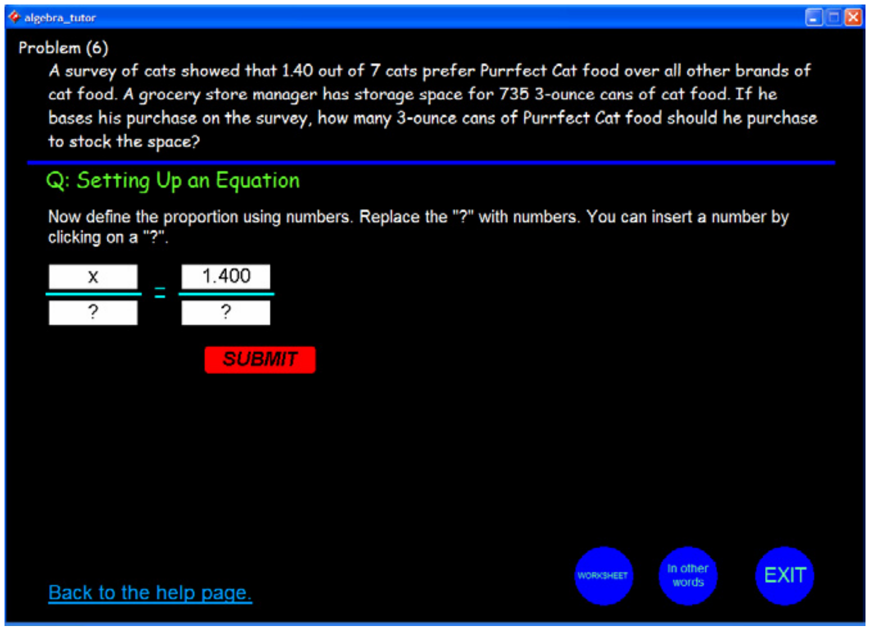

Figure 1: Sub-problem for representing the problem as an equation

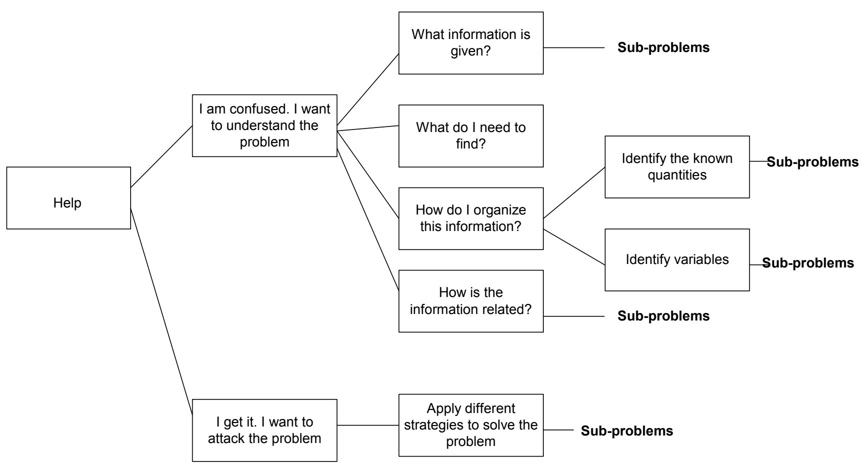

Figure 2: The network of help hyperlinks

The tutor characterizes problems according to schemas that capture the underlying conceptual structure of problems. We have identified 5 schemas that characterize most high-school Algebra word problems. The tutor includes sub-problems to help students identify a problem's schema and use this information to solve the problem. This is again based on the findings of our literature survey which showed that one characteristic that distinguishes experts from novices is that they identify problems by their conceptual structures while novices identify problems by surface features [Bansford et. al. 2000]. Encouraging students to think of the deeper problem structure was one of the design goals.

Since at-risk students often have reading difficulties, the tutor also provides reading assistance in the form of alternate, simpler re-statements of problems.

The tutor personalizes instruction in two ways: by adaptive selection of problems, and through adaptive guidance. Responding to suggestions from high-school Algebra teachers who evaluated an earlier prototype, the tutor has been re-designed to give complete navigational control to the students, letting them choose the sub-problems to attempt to help solve the problem. However, during the formative evaluations we observed that many of the students were choosing to ignore the sub-problems even if they were unable to solve the problem. Thus, some students need to be guided towards attempting the sub-problems if they are unable to solve the problems themselves. The tutor models this student behavior as a student's help-seeking trait and observes the student's patterns with respect to being able to solve the problems without assistance, or being unable to solve the problem but not seeking help, etc. When the tutor determines that the student has a tendency to not seek help when necessary, it adapts the problem-solving environment's interface to offer guidance to the student. In particular, it highlights the links to the problems so as to guide the student to attempt the sub-problems in a specific order.

We have developed a framework for defining complexity levels for problems and using student performance records to automatically tailor the complexity level so as to provide an appropriate level of challenge to students. It is well known that students learn best when presented with instructional material that is neither too easy nor too difficult. The challenge level should be sufficiently high to keep students engaged, yet low enough that students have a good chance of success with some instructional support. The tutor maintains a model of the student's mastery over a complexity level measured as the percentage of problems the student has solved successfully at each level. The mastery levels are estimated based on the most recently solved problems to account for learning effects as well as learning decay. When this mastery level exceeds a threshold, the tutor selects problems at the next higher level of complexity. When it falls below a threshold, the tutor presents easier problems.

The tutor represents the domain knowledge as a case-base of problem templates where each template is associated with skills and attributes. Each template is also associated with a set of sub-problems, solutions to the problem and the sub-problems along with an explanation of the solution. Problem templates are classified according to their complexity level. This case-based representation was chosen for its ease of development and extension. Problem templates are generalized versions of a problem where the quantities involved in the problem, and other problem entities like people's names, and jobs, etc. can be generalized by encoding them as variables that can take on ranges of values. Presenting a problem to a student involves creating a problem instance by replacing variables with values in the ranges specified. Thus, a single problem template can be used to create many instances, making it possible to present students with similar, but not identical problems for practice.

Thus, we have designed a tutor that enables student to practice their problem-solving skills in a safe, private environment where they can make mistakes without embarrassment. There is often criticism leveled at instructional strategies aimed at at-risk students that they focus too much on basic skills and do not provide them with enough challenge and training in meta-cognitive skills. The tutoring framework we have developed emphasizes providing a challenging environment with a meta-cognitive framework over basic skills training.

3 Evaluation of the ITS

The Algebra tutor was evaluated twice, but only over short periods of time. On both these occasions, students worked with the tutor for about 1.5-2 hours. Due to the limited interaction, we did not observe any significant improvements in problem-solving performance due to the tutor. On both these occasions, surveys of the students using the tutor expressed an overall positive reaction. Both these studies did yield useful information for further enhancements to the tutor. We plan to conduct larger-scale studies in the near future.

4 Related Work

In addition to a plethora of commercially available off-the-shelf computer-based teaching systems for Algebra, a number of Intelligent Tutoring Systems have also been developed [Nicaud 2000]. Many of these focus on teaching students to solve Algebraic equations [Alpert et. al. 2000, Bouhineau and Nicaud

2000]. The most widely used system is that developed by [Koedinger 2000] which focuses on problem-solving skills, and uses self-explanation as a part of its instructional approach. [Heffernan and Koedinger 2000] describe an ITS for teaching students to translate between English and Algebra. The work we have reported distinguishes itself from all the above previous work through its emphasis on meta-cognition and the promotion of meta-cognitive thinking, and its use of problem schemas.

5 Conclusion

This report describes an effort to develop an innovative meta-cognitive tutor for high-school Algebra. The tutor has been developed and preliminary evaluations have been conducted. Numerous enhancements to the tutor are envisioned. Currently, the tutor only addresses the topic of proportionality. We would like to extend it to include other topics and to include remedial instruction on basic skills. We would also like to extend the meta-cognitive aspects by including opportunities for reflection, student provided justification of solutions, and self-explanations. Enabling students to find similar, worked-out examples and helping them transfer the solution could be beneficial as well. Another area for future work is to expand on the notion of problem schemas and use them more to leverage instruction on approaching problems. Finally, we would like to add natural language dialogue capabilities to make the interface natural and easier to use.

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