Intelligent Tutoring Systems have Forgotten the Tutor: Adding a Cognitive Model of Human Tutors

Neil T. Heffernan
Computer Science Department
Carnegie Mellon University
5000 Forbes Avenue
Pittsburgh, PA 15213 USA
neil@cs.cmu.edu

ABSTRACT
I propose that a more effective intelligent tutoring system (ITS) for the domain of algebra symbolization can be made by building a cognitive model of human tutors and incorporating that model into an ITS. Specifically, I will collect protocols of humans engaged in tutoring and use these to build a model of Socratic dialogue for this domain. I will then test whether the ITS is more effective with such dialogue capabilities.

Keywords
Intelligent Tutoring Systems, ACT-R, user model, algebra, tutoring, learning, education, Socratic dialogue

INTRODUCTION
One-on-one tutoring has long been known to be dramatically more effective than both classroom instruction and traditional computer-aided instruction [3]. ITS researchers have set for themselves the goal of building computer systems that reach that level of effectiveness [2]. They have achieved much of their success by building cognitively accurate models of students. Even commercially available online tutoring systems like Microsoft's Active Assistant are beginning to appear. I propose that we can make ITSs more effective by studying human tutors and incorporating models of them into ITSs.

The Domain: Symbolization
I am building an ITS for algebra *symbolization.* Symbolization is the act of translating a problem situation into the language of formal algebra notation. Symbolization is ubiquitous: from using a spreadsheet to programming a computer. Symbolization is a key barrier to the more sophisticated use of computers. This skill is of particular interest to the CHI community: we cannot take advantage of innovations like end-user programming languages unless users are able to translate into symbols the problems they wish to solve. Symbolization is usually introduced to students by starting with simple word problems like the following:

> Ann is in a rowboat and starts out 800 yards from the dock. She rows towards the dock for "m" minutes but then stops to rest. Her rowing speed was 40 yards per minute. Write an expression for her current distance from the dock.

Problem 1. The answer is "800-40*m"

© 1998. Copyright on this material is held by the author.

Socratic Dialogue for Symbolization
Researchers at Carnegie Mellon University have already built an ITS, called PAT, that attempts to teach all of high school algebra including symbolization [6]. Currently the cognitive student model in PAT treats symbolization as a single atomic skill. But even though its output is a single expression, symbolization appears to require a composite set of skills. I have done research, described below, which shows symbolization actually involves many complex processes including comprehending the story, building up a representation of the quantitative structure and finally outputting the correct symbols [5]. Therefore I call symbolization a compound skill, in that it is not a single skill but the result of a chain of reasoning. Since a student might have trouble anywhere along that chain of reasoning, current ITSs that produce a single hint are unlikely to be effective. One response of ITS designers to a compound skill has been to change the interface to force the student to state his intermediate results, much as Corbett & Anderson [4] redesigned their LISP tutor to have students reify their subgoals before they write their program. One worry is that students will be confused by the extra interface components, impeding learning and transfer. Another concern is that the task becomes too easy when broken into parts.

My approach is inspired by preliminary protocol analyses that suggest that tutors enter into a dialogue to help the student when the student is unable to succeed. Lepper et. al. observe that tutors use a demanding scaffolding approach whereby they start by asking general questions that leave the students to do most of the work and then only proceed to use more specific questions if the student still has difficulty [7]. This Socratic dialogue approach is further supported by Lepper's observation that 80-90% of tutorial utterances (for the domain of arithmetic) were in the form of questions. Although a completely general method of Socratic tutoring would require full natural language processing, we are able to take advantage of a feature of word problems: it is possible to understand a lot of what students are thinking by interpreting only the algebraic expressions they write. Therefore we can avoid some hard natural language processing problems and yet still carry on an intelligent dialogue.

The Need to Model Tutorial Reasoning
In order to conduct a dialogue with a tutee, what factors does a tutor need to reason about? It is increasingly recognized that tutors do a lot more than diagnosing and reporting bugs. Tutors show evidence of understanding the stu-

dent's misconceptions but do not report these "bugs" directly [7]. Consequently, we do not want to throw out the student model because tutors must do some diagnosis in order to figure out what is the next best question to ask the student. Therefore, we need to model the complex processing that allows a tutor to decide what tutoring strategy to use. The tutor model should also attempt to reason about 1) what is the best way to word a response, 2) when to provide declarative instructions, 3) the motivational state of the student and 4) the next best problem to try.

Completed Research: The Cognitive Student Model

I have conducted empirical studies [5] that have led to the construction of a cognitive student model of symbolizing. I collected data from 80 subjects who symbolized word problems that were carefully constructed to determine what factors most affected the difficulty of symbolizing. This research also determined the relative difficulty of these factors. This research was fruitful and led to results that any model of symbolizing must be able to account for. I currently have an ACT-R [1] student model that is able to account for the major trends in the data. This model of symbolization predicts how people decompose this task and has led to a suggested improvement of the scaffolding in PAT, the current ITS. I have also analyzed the errors students made and am using these to parameterize the model to fit the average student's performance. This model is capable of diagnosing a student's input and figuring out what sorts of misconceptions the student is expected to have.

PROPOSED MODELING OF THE TUTOR

I propose to collect protocols from experienced tutors while they are tutoring students. Through protocol analysis I will first categorize the common tutorial strategies they use. I will develop a taxonomy that attempts to get a broad coverage of these tutorial strategies. Preliminary protocol analysis has already revealed one of those strategies illustrating what I call a sub-dialogue in the context of Problem 1. The sub-dialogue is a multi-step plan which attempts to scaffold the symbolization skill by building off the skill of computing values. It would continue to the point of getting the student to say "800-40*m."

Student: 800m
Tutor: No. Let me ask you an easier question. Suppose the number of minutes she had been rowing was "3" instead of "m". What would be the distance to the dock?
Student: 680
Tutor: Correct. Can you show the math for how you got that?
Student: 800-120
Tutor: That is partially correct. How did you get the 120?
Student 40*3
Tutor: Good. Now write how you got the 680 again, but this time use 40*3 in place of 120.

This is just one of the dozen of scaffolding strategies I have witnessed tutors using. A few others include

- Sub-dialogue to symbolize sub-quantities like "40*m" before asking for super-quantities like "800-40*m"
- Feedback pointing out typical "bugs" or mistakes.
- Tutorial on error-checking strategies.

We have also noticed that tutor dialogues are reactive. If the student makes a mistake on some point, the tutor might decide to use another strategy to help correct that misconception before getting back to his overall plan. In this way a tutor can handle embedded digressions.

After developing a taxonomy of these strategies I will build an ACT-R model that is capable of performing them. Then the next step is to getting the model to choose the correct strategy in the correct circumstances. As input the tutor model will accept the diagnosis from the student model and will then perform reasoning to select which strategy to use. In addition the tutor model will take as input the context of the dialogue, the state of the tutor's estimate of the student's knowledge, and the success and use of the various strategies. I will then use ACT-R's conflict resolution mechanism to allow the system to learn what strategies work best for each student.

Empirically answerable questions

By combining my student model with my tutor model, I will have an ITS and will test its effectiveness against the existing ITS, PAT. This project will indicate what architectural enhancements are needed to allow an ITS to carry on human-like dialogues. Also, this functioning tutor model will serve as a flexible research tool to allow me to easily investigate some other learning issues such as "what are the best tutorial strategies", and "does having a variety of strategies to teach the same thing improve learning?"

REFERENCES

1. Anderson, J. R.. *Rules of the Mind*. Hillsdale, NJ: Erlbaum (1993).
2. Anderson, J. R., Corbett, A. T., Koedinger, K. R., & Pelletier, R.. Cognitive tutors: lessons learned. *The Journal of the Learning Sciences*, (1995) 4 (2), 167-207.
3. Bloom, B. S., The 2-sigma problem: The search for methods of group instruction as effective as one-to-one tutoring. *Educational Researcher* (June 1984), 4-16.
4. Corbett, A. T., and Anderson, J. R., Knowledge decomposition and subgoal reification in the ACT programming tutor, in Proceedings of Artificial Intelligence in Education (1995) 469-476
5. Heffernan, N. T., and Koedinger, K. R. The composition effect in symbolizing: the role of symbol production vs. text comprehension. *Proceedings of the Cognitive Science Society* (1997), 307-312.
6. Koedinger, K. R., Anderson, J. R., Hadley, W. H., & Mark, M. A. (1995). Intelligent tutoring goes to school in the big city. In *Proceedings of the 7th World Conference on Artificial Intelligence in Education*, (pp. 421-428). Charlottesville, VA: Association for the Advancement of Computing in Education.
7. Lepper, M. R., Drake, M. F., and O'Donnell-Johnson, T. Scaffolding techniques of expert tutors, in *Scaffolding Student Learning: Instructional Approaches and Issues.* (ed) Hogan, K., and Pressley, M. Brookline Books, Cambridge, MA. 1997.