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Rule-based expert systems to support step-by-step guidance in algebraic problem solving: The case of the tutor PAT2Math



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ABSTRACT

In order for an Intelligent Tutoring System (ITS) to correct students' exercises, it must know how to solve the same type of problems that students do and the related knowledge components. It can, thereby, compare the desirable solution with the student's answer. This task can be accomplished by an expert system. However, it has some drawbacks, such as an exponential complexity time, which impairs the desirable real-time response. In this paper we describe the expert system (ES) module of an Algebra ITS, called PAT2Math. The ES is responsible for correcting student steps and modeling student knowledge components during equations problem solving. Another important function of this module is to demonstrate to students how to solve a problem. In this paper, we focus mainly on the implementation of this module as a rule-based expert system. We also describe how we reduced the complexity of this module from $O(n^d)$ to $O(d)$, where n is the number of rules in the knowledge base, by implementing some meta-rules that aim at inferring the operations students applied in order to produce a step. We evaluated our approach through a user study with forty-three seventh grade students. The students who interacted with our tool showed statistically higher scores on equation solving tests, after solving algebra exercises with PAT2Math during an approximately two-hour session, than students who solved the same exercises using only paper and pencil.

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1. Introduction

Intelligent Tutoring Systems (ITSs) have shown promising results when applied as a supplemental classroom learning tool (Koedinger, Anderson, Hadley, & Mark, 1997; Nicaud, Bittar, Chaachoua, Inamdar, & Maffei, 2006; Nicaud, Bouhineau, & Huguet, 2002). Large-scale experiments in high-schools demonstrated that ITSs can improve students learning (Koedinger et al., 1997; Koedinger & Sueker, 1996). The success of this type of educational software is due to the fact that it can offer important features to personalize the learning processes such as one-on-one learning, immediate personal feedback, demonstration of problem solving when students are having difficulty, and assessment of students' skills.

Vanlehn (2006) describes the tutor as having two loops. The *outer loop* is responsible for deciding the sequence of exercises or problems for students to work on. The *inner loop* provides step-by-step guidance during problem solving activity.

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In order to provide immediate feedback in the inner loop, an ITS' architecture is generally composed of an expert system module (ES) that is able to solve the same type of exercises that students should do in multiple ways. Thus, for each step of the problem the system compares the answer provided by a student with the expert system's solutions (an answer may have several correct solutions) and checks whether they are equivalent. If the ES can generate or test all possible solutions to a given problem, then it can identify when a student has taken an incorrect path to solve the given problem and offer immediate feedback (generally colored labels are presented to indicate whether or not the student's answer for a given step is correct) (Heffernan, Koedinger, & Razzaq, 2008). Some tutors provide additional resources (e.g. explanations or hints) when students are having difficulty or solving the problem or arriving at the correct answer.

In fields such as math and physics, the knowledge is usually implemented as a rule in the form: "if (*condition is true*) then (*do action A*)". Each rule represents an operation that can be applied in a step to solve a problem. The ES inference engine scans the base searching for rules to be triggered, i.e. rules whose conditions are satisfied by the current step of the solution.

In addition to providing appropriate feedback to students, the rules also contain information about the related knowledge components. For example, a rule can represent the process (knowledge component or skill) of “subtracting an integer b on both sides of the equation”. Thus, when the ES module corrects a student step solution, it is able to provide the student model with information about the skills necessary to solve that step. The student model uses this information to infer which skills students have mastered and which they need to practice more. This allows the tutor to create personalized hints in the inner loop and also to select more appropriate exercises for students to solve (outer loop).

Although there are well known algebra tutors (Chaachoua, Nicaud, Bronner, & Bouhineau, 2004; Cohen, Beal, & Adams, 2008; Koedinger & Sueker, 1996; Melis, Goguadze, Libbrecht, & Ullrich, 2009), few of them have an expert system module that is able to solve exercises and provide step-by-step guidance (Chaachoua et al., 2004; Koedinger & Sueker, 1996), an essential feature for a learning system to be classified as an ITS, according to (Vanlehn, 2006). Furthermore, previous work does not explore in detail how to implement an expert system module, which artificial intelligence knowledge representation format needs to be used, when an inference mechanism should be triggered and how to solve some inherent computational complexity problems.

This paper presents the ES of the algebra tutor PAT2Math. PAT2Math is an intelligent tutor system that teaches students how to solve linear and quadratic equations. It is a web system implemented in Java, which allows students to use it in any computer or platform with Internet access. PAT2Math is composed of an algebra editor (PATEquation), which assists students in solving equations.

The ES has an essential role in PATEquation; it is responsible for providing immediate feedback to students at every step of their problem solving. Our main goal is to present this module knowledge and explain how to the ES implements problem solving and provides the student with step-by-step guidance. We describe how to reduce the complexity of this module from $O(n^d)$ to $O(d)$, where n represents the number of rules in the knowledge base, by using meta-rules that guide the inference of the operations student applied to produce a step. We finish this paper by presenting the results of a user study we conducted with forty-three 7th grade students who interacted with PATEquation for three classes.

This paper is organized as follows. Section 2 describes problem solving under a pedagogical perspective. Section 3 presents the current state of the art in Algebra Intelligent Tutoring Systems. In Section 4, we explain the main artificial intelligence techniques used to develop ITS expert systems. In Section 5, we describe PAT2Math, the Algebra Tutor that our research group is developing. PATEquation, the problem solving editor of PAT2Math, is presented in Section 6. The ES responsible for providing step-by-step guidance in PATEquation is described in Section 7. The experiment design and results are reported in Section 8. Finally, Section 9 presents our conclusions.

2. Solving algebraic problems

An Algebra task is generally a word problem for the student to solve. An algebraic word problem consists of one or more sentences representing a situation or a story, where the student needs to understand the elements in order to generate a mathematical model to represent it. The model consists of one or more equations that the pupil should solve in order to obtain the numerical values that are the solution of the problem (Gama, 2004). Take for example the word problem below (adapted from Munem & West (2003, p. 107)):

“A computer store sells desktop and laptop computers. Due to space considerations, the number of laptops in inventory is seven less than twice the number of desktops in stock. How many desktops does the store have if it has a total of 272 computers?”

The process of solving a word problem has two phases (Mayer, 1999; Polya, 2004): (i) the Problem Representation (also called Symbolization (Heffernan, Koedinger, & Razzaq, 2008)), and (ii) the Problem Solution. While the former concerns to the transformation of algebra word problems into a system of equations, the second encompasses the process of solving these equations using algebraic operations.

For example, for the word problem that we previously presented, the student could provide the following solution:

$$x + (2x - 7) = 272 \quad (1)$$

$$3x - 7 = 272 \quad (2)$$

$$3x = 279 \quad (3)$$

$$x = 93 \quad (4)$$

In the example above, line (1) refers to the process of Problem Representation, and lines (2–4) to the Problem Solution phase. As shown in the above solution, solving a task involves several steps. Each line provided by the student in the above solution is a step.

A step can involve the correct use of one or more Knowledge Components (KC) (also called knowledge units (Alevin, McLaren, Sewall, & Koedinger, 2009)). It comprises any unit into which the knowledge can be broken down, such as rules, concepts, facts, and procedures (Vanlehn, 2006). For instance, in order to arrive at line (2) in the above example, the student applied the operation (or KC) “add variable coefficients” in line (1) of the equation.

In the next section, we will describe the main Algebra Intelligent Tutoring Systems and the tools and types of feedback they offer to help students solve algebra word problems in these two phases.

3. Algebra Intelligent Tutoring Systems

The field of ITS has shown significantly improvements since the emergence of the first systems in the eighties (Woolf, 2009). The evolution of the Internet, the increasing performance of computers, and improvements of artificial intelligence techniques and tools have furthered the development of ITSs in several domains, such as Physics, Math, Medicine and others (see (Woolf, 2009) for an overview).

Previous work has largely been applied in classroom settings, demonstrating they can improve student performance on standardized and experimenter-designed tests by one-half to two standards deviation (Cohen et al., 2008; Koedinger & Sueker, 1996; Shelby et al., 2000). Some of the most known research focused on the Algebra content domain. This is the case of Cognitive Algebra Tutor (previously PAT) (Koedinger & Sueker, 1996), Aplusix (Nicaud et al., 2006, Nicaud, Bouhineau, & Huguet, 2002), ActiveMath (Goguadze & Melis, 2008; Melis, Goguadze, Libbrecht, & Ullrich, 2009) and AnimalWatch (Birch & Beal, 2008; Cohen et al., 2008). We believe there are two main reasons for this. First, Algebra is a content domain (or task domain (Vanlehn, 2006)) in which a great number of students experience poor achievement (Carpenter, Kepner, Corbitt, Lindquist, & Reys, 1982; National Commission on Excellence in Education, 1983). Secondly, it requires less effort to formalize math content into computer algorithms, because it is mainly composed of procedural content, which can be easily represented by computer algorithms. In the end of this section, we describe the main algebraic tutors proposed by the Artificial Intelligence and Education community.

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