The Conceptual Helper: An Intelligent Tutoring System for Teaching Fundamental Physics Concepts

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Abstract. This paper describes an intelligent tutoring system designed to help students solve physics problems of a qualitative nature. The tutor uses a unique cognitive based approach to teaching physics, which presents innovations in three areas. 1) The teaching strategy, which focuses on teaching links among the concepts of the domain that are essential for conceptual understanding yet are seldom learned by the students. 2) The manner in which the knowledge is taught, which is based on a combination of effective human tutoring techniques, successful pedagogical methods, and less cognitively demanding approaches. 3) The way in which misconceptions are handled. The tutor was implemented using the model-tracing paradigm and uses probabilistic assessment to guide the remediation. Some preliminary results of the evaluation of the system are also presented.

1 Introduction

Several studies conducted during the past fifteen years revealed that students in traditional elementary mechanics classes can master problem solving of a quantitative nature, but perform poorly in solving qualitative problems [Halloun & Hestenes, 1985; Hake, 1998]. (An example of a quantitative problem is "A 2kg create slides down a frictionless inclined plane. Determine the acceleration of the crate given that the angle of the plane is 30 degrees." An example of a qualitative problem can be seen in Figure 1.) Moreover, students' naïve conceptions of physics remain intact after finishing their classes, having not been modified or replaced by the newly acquired scientific knowledge.

A few approaches have been proposed to improve this situation, though none has met with great success [Hake, 1998]. Considering that elementary mechanics is a required course for almost all science majors, the above results make it clear that there is a need to improve the instruction of the subject. Toward this end, we developed an intelligent tutoring system, called the Conceptual Helper, which presents a novel cognitive-based approach to teaching conceptual physics. The Conceptual Helper coaches students through homework problems in the area of Newtonian mechanics that deals with linear motion and projectile motion in kinematics and dynamics.

The Conceptual Helper is part of a larger enterprise called Andes [VanLehn, 1996; Gertner et al., 1998]. Andes is basically an immediate feedback model-tracing tutor designed to coach first year physics students through problem solving. It has three help systems. A Procedural Helper that provides procedural help during quantitative problem solving. A Conceptual Helper [Albacete, 1999] that teaches conceptual knowledge of the subject matter to students and tries to get them to abandon

misconceptions (this system is described herein). And a Self-Explanation coach that guides students through example studying. At present, each help system works in isolation; however in the future the Conceptual Helper and the Procedural Helper will work cooperatively in an attempt to integrate conceptual and quantitative problem solving.

Two steel balls, one of which weights twice as much as the other, roll off of a horizontal table with the same speeds. In this situation:
a) both balls impact the floor at approximately the same horizontal distance from the base of the table.
b) the heavier ball impacts the floor closer to the base of the table than does the lighter.
c) the lighter ball impacts the floor closer to the base of the table than does the heavier.

Fig. 1. Example of a qualitative problem.

2 The Conceptual Helper from a Technical Point of View

The Conceptual Helper follows the model-tracing paradigm. In its simplest form a model-tracing tutor contains a cognitive model that is capable of correctly solving any problem assigned to the student. Then the technique basically consists of matching every problem-solving action taken by the student with the steps of the expert's solution model of the problem being solved. This matching is used as the basis for providing ongoing feedback to students while they progress through a problem. In the Conceptual Helper when the students make a correct action, the input is turned green to emulate the typical confirmation given by human tutors. On the other hand, when the action is incorrect the input is turned red and some specific feedback is provided.

One tool that the tutor uses to decide what knowledge to teach the student when he makes a mistake is the student model. The student model is represented by a Bayesian network. Each node in the network represents a piece of conceptual knowledge that the student is expected to learn or a misconception that the tutor can help remedy. For example, a node in the network is "if the velocity of an object is constant, then its acceleration is zero." Each node in the network has a number attached to it which indicates the probability that the student has mastered it. In the case of misconceptions the probabilities represent the likelihood that the student holds such a misconception. As the student solves a problem, the probabilities are updated according to the actions taken by the student and the feedback provided by the tutor.

The Conceptual Helper makes use of the student model in deciding which pieces of knowledge it should try to teach to the students and when it should do so. When the student makes a mistake while solving a problem, and the probability of his knowing the corresponding piece of correct knowledge is higher than 0.8, then the tutor will not try to teach it. It will just turn the entry red and then store a short explanation as to what was incorrect. This explanation could be accessed by the student by selecting "what is wrong with that?" from a help menu. However, if the probability of the student's knowing the corresponding piece of knowledge is lower than 0.8, then the Tutor will try to convey the corresponding knowledge to the student. In the case when the mistake is most likely attributed to a known misconception, the helper just tutors the student on it. The logic behind this decision is that misconceptions are rarely encountered more than once; hence regardless of the probability of the student harboring such a misconception, it is safer to clarify it.

3 The Teaching Strategy Followed by the Conceptual Helper

The Conceptual Helper has two main goals: to teach qualitative physics, and to try to get the students to abandon common misconceptions.

To accomplish its first goal, the Conceptual Helper follows a novel teaching strategy that concentrates on teaching students the *links* that connect the domain's concepts of interest rather than the concepts in themselves. This strategy is based on the cognitive science theory which describes the knowledge base of experts as well structured and *highly connected* (e.g., Chi & Koeske 1983). Several studies (e.g. Van Heuvelen, 1991) suggest that the knowledge of students when they begin an introductory physics course typically consists of a small number of unstructured, disconnected facts and concepts, and they leave the courses with more facts and concepts but their knowledge is equally disconnected and unstructured. Hence the teaching strategy tries to build the students' knowledge bases akin to that of experts.

The links between the concepts of any domain can be of various different types. The word "links" has been traditionally used in Semantic Networks to describe two-place predicates such as "is-a" or "part-of". However, we use the word "links" to describe rich qualitative rules that integrate pieces of knowledge. The kinds of links that the Conceptual Helper focuses on are those which can be inferred from the principles or from the definitions of the concepts of the domain. For example, one of the target links is "the direction of the net force applied to an object is the same as the direction of the object's acceleration." This connection between the concept of acceleration and the concept of net force can be inferred from Newton's second law. Likewise, the link "if the acceleration of an object is zero, then the object's velocity is constant" can be inferred from the definition of the concept of acceleration. These types of links are not evident to the students, in the sense that, even if students can repeat without hesitation the definition of acceleration and Newton's second law, by and large, they are generally not able to assert the links between concepts that follow from those definitions [Reif, 1995]. However, these types of links are essential for reasoning qualitatively about the motion of objects and for solving the qualitative problems. Additionally, the tutor helps students understand some concepts in themselves, such as the concepts of normal force and friction force.

The second goal of the Conceptual Helper is to help students replace their misconceptions with scientifically correct knowledge. The word "misconception" is taken to mean the knowledge that the students bring to the class, having acquired it through interaction with the world's physical phenomena, but that does not agree with scientific knowledge. For example, in Figure 1 the problem is designed to uncover the misconception that weight influences the horizontal motion of an object. The Conceptual Helper handles misconceptions by presenting students with the basic line of reasoning underlying the correct interpretation of the phenomena that are the base of the misconception. This is as opposed to using discovery environments or computer-simulated experiments, which are the two common ways in which teachers have tried to correct misconceptions. We believe that it is not setting up the (simulated) equipment, making the runs, recording the data, and inducing a pattern that convinces a student of a certain piece of knowledge, but rather the line of argument itself. Knowing the correct line of reasoning enables the student to self-explain the phenomenon. An example can be seen in Figure 6.

4 The Libraries of Lessons and Dialogues to Convey Knowledge to the Student

According to the teaching strategy that the Conceptual Helper follows, its main goal is to make sure the student both learn the links that connect the concepts of interest of the domain and abandon common misconceptions. To accomplish this task, it uses two different kinds of interactions with the student, namely dialogues and mini-lessons. Both of these were intended to emulate human tutors as closely as possible, to incorporate some pedagogical techniques that have proven to be effective and to present the knowledge in a way that is less cognitive demanding. To clarify their use the examples given will refer to the problem shown in Figure 2.

Mini-lessons and dialogues were automatically generated from templates where objects, motion directions and graphics were instantiated as needed.

A coin is tossed upward. Considering that there is no effect of air resistance, draw a motion diagram[1] for the coin from the time it is released until it reaches its apex.

Fig. 2. Example of a qualitative problem requiring an explicit solution.

4.1 The Dialogues

When the student makes a mistake while solving a problem, which is judged as not coming from applying a misconception (see definition of misconception in section 3), the tutor will try to correct this mistake by helping the student build the *link* between a known concept and the concept corresponding to the correct action. One of the ways in which the tutor does this is by engaging the student in a short dialogue, emulating the behavior of human tutors when they use hints and leading questions [Fox, 1993].

The dialogue consists of two statements. Each statement is incomplete, but has a menu from which the student can select a completion. The first statement in the dialogue is aimed at eliciting from the student the value of the antecedent of the target link. Conversely, the second statement is aimed at getting the student to provide the consequent of the link. An example of a dialogue can be seen in Figure 3. In the example, the link of interest is: "if (in a linear motion) the velocity of an object is decreasing then the object's velocity and its acceleration have opposite directions."

This is how the dialogues are used. Suppose that a student is solving the problem shown in Figure 2 and that he draws the velocities correctly as pointing up and decreasing, but then he draws the acceleration with an upward direction. Then the tutor turns the input red and verifies that it does not correspond to a misconception. If it does not, the Conceptual Helper finds in the solution graph of the current problem the rule that the student should apply to correct its error and which is on the most likely solution path[2] that the student is following. If the probability of the student

[1] A motion diagram consists of describing the position, velocity and acceleration of the system of interest at regular time intervals. The description is achieved through drawing the corresponding vectors.

[2] The system has a program capable of estimating the most likely solution path that the student is following.

Reminder lessons. The reminder lessons are aimed at refreshing the student's memory of a piece of knowledge. They consist of a textual explanation of the target knowledge which is presented at a more general level. Also, there is no detailed tailoring to the particulars of the problem as there is with explanatory mini-lessons. An example of this kind of lesson can be found in Figure 5 (this is the reminder mini-lesson corresponding to that presented in Figure 4).

> Acceleration is a vector defined as the rate of change in velocity with time. You can think of the acceleration vector as what changes the velocity vector. Acceleration can change the velocity's magnitude, its direction, or both.
> In this case, the magnitude of the velocity is decreasing. For that to happen in a linear motion, the velocity vector and the acceleration, have to have opposite directions.

Fig. 5. Example of a reminder mini-lesson.

Reminder lessons are used by the tutor when it has already presented the corresponding detailed mini-lesson, but the student has made a mistake which involves applying the same piece of knowledge. The belief is that, if the student has already received a detailed explanation of the knowledge of interest while solving a problem, but he fails to use it properly in a further step, then a reminder of the knowledge should suffice to get the student to correct his mistakes. This models human tutors as they progressively fade away the support they give to students [Collins et al., 1989].

Mini-lessons that summarize knowledge. When students finish solving a problem, they click on a *done* button. When this happens, the Conceptual Helper presents to the student a mini-lesson that summarizes the most important pieces of knowledge that were used to solve the current problem. The summary mini-lessons were designed to include only a few main ideas based on studies which suggest that very detailed explanations after completion of problem solving can be confusing for the students [Katz & Lesgold, 1994].

There are three main reasons why the tutor uses summary mini-lessons. The first is that, because the student in not engaged in problem solving anymore, he may be more receptive to thinking about specific pieces of conceptual knowledge than while trying to finish the problem [Katz et al., 1996]. The second is that the student could have solved parts of the problem by just guessing. Hence going through the pieces of knowledge that he should know might help rectify the guessing. The third reason for using summary mini-lessons is that, if the student made several mistakes while solving the problem, he may not recall all the corrections made by the tutor and which were really relevant and worth remembering (students may make mistakes that are related to the use of the interface and not to their knowledge of physics). The summary of knowledge presented in the mini-lesson may help in this respect.

Mini-lessons that address misconceptions. Misconceptions are addressed both during regular problem solving and through multiple choice questions. The explanations presented in this kind of mini-lesson are aimed at replacing the student's misconception. They follow the philosophy presented in the teaching strategy (section 3). They consist of a line of reasoning that is based on the scientific knowledge that the student should follow to self-explain the phenomenon of interest. An example of this kind of lesson can be seen in Figure 6. It is the mini-lesson a student would receive if, for example, he clicked on answer b) of the problem presented in Figure 1.

In the case of multiple-choice questions, the tutor will present a mini-lesson regardless of whether the student's answer choice is correct or not. The only difference is in the introductory sentence which states the correctness of the answer.

> Your answer is incorrect. Here is why.
> We will begin by analyzing the vertical motion of both balls. The only force acting on each ball, on the vertical direction, is its weight. If you apply Newton's second law F=ma, in the vertical direction, you get $w_1=m_1g$ for the first ball and $w_2=m_2g$ for the second ball. Therefore, the acceleration of both balls, in the vertical direction, is g, even if the weight of one ball is twice the weight of the other ball.
> You may recall that acceleration is what changes velocity. In this case, the acceleration will make the vertical velocity of the balls increase. And since both balls have the same acceleration, their velocities will vary at the same rate. This means that at any instant, on their trip down, they will have the same vertical velocity. Hence, both balls will cover the distance in the same amount of time.
> Now, let's analyze the horizontal motion of the balls. The only force acting on the balls is their weight, which is straight down. Hence, if we apply Newton's second law in the horizontal direction for each ball we find that the acceleration is zero because the total force in that direction is zero. Additionally, the problem states that both balls have the same horizontal velocity. And since the acceleration is zero, the velocity of both balls is constant. Additionally, we know from the analysis of the vertical motion of the balls that it takes both balls the same amount of time to get to the ground. Hence if both balls fly with the same horizontal velocity for the same amount of time they will travel the same horizontal distance. In other words, both balls will hit the ground at approximately the same horizontal distance from the base of the table.

Fig. 6. Mini-lesson addressing the misconception "Influence of weight on horizontal motion"

5 Preliminary Analysis of the Evaluation of the System

An evaluation of the system was conducted to test its effectiveness. To this end 42 students taking Introductory Mechanics classes were recruited and randomly divided into a Control group and an Experimental group. Both groups took a paper-and-pencil pre-test that consisted of 29 qualitative problems, 15 of which belonged to the Force Concept Inventory test[3]. Then they solved some problems with the Andes system receiving appropriate feedback according to the group they belonged to. The students in the Control Group had their input turned green or red depending on the

[3] The Force Concept Inventory test has become the standard across the US to measure conceptual understanding of elementary mechanics [Hake, 1998].

correctness of the entry. Then, in the case of an incorrect action, the students could ask for help making a choice from a help menu. The kind of help they received consisted of simple hints such as "the direction of the vector is incorrect" or just telling them the answer. On the other hand the students in the experimental group received the green/red feedback depending on whether their action was correct but when the input was incorrect the Conceptual Helper intervened as explained above. After the students finished solving the problems with the system they took a post-test which was the same as the pre-test with the exception of a few changes in the cover stories of some problems.

A preliminary analysis of the data found that the mean gain score (the subject's post-test score minus his or her pre-test score) of the control group was 4.12 with a standard deviation of 5.33, while the mean of the experimental group was 7.47 with a standard deviation of 5.03 -a statistically significant difference ($t(40)=2.094$, $p=0.043$). Before this calculation was made, a comparison of the pre-test scores was performed and no statistically significant difference was found between the two groups ($t(40)=0.965$, $p=0.34$). The statistically significant difference found between the means of the gain scores suggests that the intervention of the Conceptual Helper had a positive impact on the students' understanding of the concepts as well as on their ability to abandon common misconceptions.

Additionally the effect size was calculated. Effect size is a standard way to compare the results of one pedagogical experiment to another. One way to calculate effect size, used in Bloom (1984) and many other studies, is to subtract the mean of the gain scores of the control group from the mean of the gain scores of the experimental group, and divide by the standard deviation of the gain scores of the control condition. That calculation yields (7.47-4.12/5.33 = 0.63). The effect size of 0.63 was comparable with peer and cross-age remedial tutoring (effect size of 0.4 according to Cohen et al., 1982). Some better results have been obtained with interventions that lasted a whole semester or academic year. For example, Bloom (1984) found an effect size of 2.0 for adult tutoring in replacement of classroom instruction and Anderson et al. (1995) reported an effect size of 1.0 for their tutoring systems. However, the results reported here were achieved with only two hours of instruction.

6 Conclusions

An intelligent coach was described which presents a novel cognitive-based approach to teaching conceptual physics. Moreover, the manner in which the desired knowledge is presented embeds many successful human tutoring techniques, such as providing hints and supporting post-problem reflection, as well as effective pedagogical techniques, like the use of a microscopic view of matter, and techniques that seem to be less cognitively demanding such as the use of anthropomorphism.

A preliminary analysis of the evaluation of the system is encouraging since it seems to reveal that the proposed methodology can be effective in accomplishing the task it was designed to perform.

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knowing the piece of knowledge is lower than 0.8, as revealed by the student model, the tutor presents to the student the first statement of the dialogue.

The velocity of the coin is: *menu choice*:	increasing decreasing constant I don't know
Therefore, the coin's acceleration and its velocity have:	opposite directions equal directions none of the above

Fig. 3. Example of a dialogue used by the Conceptual Helper.

If the student completes the first statement incorrectly the Tutor will try to teach an alternative rule, if such a rule exists. To this end it will present a dialogue corresponding to this second rule. On the other hand, if the student completes the first statement correctly, the second statement comes up. If the student gives the correct completion, he is informed of it and nothing else happens. On the other hand, if the student answers it incorrectly the Conceptual Helper evaluates what further intervention it will pursue as it is explained in the next section.

4.2 The Mini-Lessons

The main way in which the tutor explains knowledge to the student is through the use of short lessons, which are called mini-lessons. There are four kinds of mini-lessons.

Mini-lessons that explain a particular link or a concept. Suppose that a student solving the problem of Figure 2 draws the velocity correctly at two time points but then he draws the acceleration incorrectly pointing upward. Moreover, suppose the Conceptual Helper has already tried to help the student by hinting with the dialogue shown in Figure 3 but that the student has completed the second statement incorrectly. At this point, the tutor will try a more directive intervention, like a human tutor would do [McArthur et al., 1990] by presenting the student with an explanation of the knowledge of interest through the mini-lesson shown in Figure 4.

Most mini-lessons consist of a short piece of text and a graphic or animation, which illustrates what the text describes. The textual part of the mini-lesson begins with a general definition of the concept or principle that constitutes the theoretical basis for the existence of the link of interest. For example, in Figure 4, the definition of acceleration is given as the theoretical basis for explaining the relationship between acceleration and velocity. When appropriate, this abstract definition is followed by an anthropomorphic interpretation. In this example, for instance, the definition of acceleration is brought to life by making the acceleration an agent in changing the velocity. Next, a general definition of the link of interest is presented as well as its application to the particulars of the problem. In the example, this comprises the second paragraph. Additionally, when there is an animation or graphic, a brief explanation is included to highlight the knowledge of interest. Furthermore, the text has some words or phrases, such as the question at the bottom of Figure 4, that are

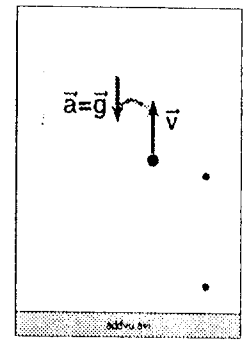
hyperlinks. By clicking on them, the student can find information or pursue a further dialogue with the tutor regarding the underlined topic.

The graphics and animations of the mini-lessons were designed with two main ideas in mind: a) people tend to reason with objects belonging to the material ontology [Chi, 1992], and b) people tend to provide anthropomorphic explanations of how the physical world works [diSessa, 1993; Rochelle, 1992]. Additionally, a microscopic view of matter was used when appropriate [Murray et al., 1990].

Acceleration is a vector defined as the rate of change in velocity with time. You can think of the acceleration vector as what changes the velocity vector. Acceleration can change the velocity's magnitude, its direction, or both.

In this case, the magnitude of the velocity of the coin, i.e., its speed, is decreasing. The acceleration is making it shorter. For that to happen in a linear motion, the velocity vector and the acceleration, have to have opposite directions.

In the animation below, you can see the acceleration vector, with an imaginary arm, making the velocity vector shorter. Notice that the velocity and the acceleration have opposite directions.



<u>Why is the speed of the coin decreasing?</u>

Fig. 4. Example of a mini-lesson explaining one relationship between the concepts of velocity and acceleration for the problem shown in Fig. 2.

To implement the first of these ideas, it was decided that the tutor would use vectors as much as possible when presenting graphical explanations of the abstract concepts whose connecting links it is trying to teach. Vectors are the correct scientific representation of the concepts and their representation as arrows is concrete, amenable to direct manipulation and has all of the characteristics of material objects. Hence this may facilitate the understanding of the knowledge.

In addition, since people spontaneously use anthropomorphism to explain how objects behave we believe that incorporating this technique into the explanations that the Conceptual Helper gives would make learning the target knowledge less cognitive demanding. Furthermore it may facilitate the production of explanations that the students generate to themselves, which has been argued [Chi, 1996] to be an effective means for learning.