Student Modelling with Confluences

Daniel Baril, Jim E. Greer and Gordon I. McCalla

ARIES Laboratory
Department of Computational Science
University of Saskatchewan
Saskatoon, CANADA S7N 0W0

Abstract

Student modelling is not typically concerned with representing the deep mental models a student employs in dealing with the world around him/her. In this research we discuss an intelligent tutoring system, PRESTO, whose goal is to understand the mental model a student has of a physical device, and then use this mental model in providing help to overcome misunderstandings related to the functioning of the device. The mental model is extracted from the student by asking questions about the relationships of variables affecting the physics of the device. The mental model is represented using deKleer and Brown's qualitative confluence equations. The mental model can then be compared to a set of confluences representing a correct perspective on how the device functions. A variety of pedagogical choices can be made: to explain contradictions implicit in the student's understanding of the device, to show the student a simpler physical device that by analogy illustrates anomalies in the student's understanding, or to let the student witness his/her version of the device in operation so the misunderstandings become obvious. Experiments in running PRESTO with a number of students shows this approach to mental modelling to be promising.

Introduction

Human tutors are able to determine from a student's description of how a physical device works the underlying misconceptions that the student has about the physical properties that govern the device's behaviour. To do this the tutor might present the student with a physical device and elicit from the student a description of how that device functions. From the student's description the tutor is able to construct a set of beliefs about the student's beliefs. In other words, the tutor constructs a representation of the student's mental model of the physical device. This representation allows the tutor to predict answers that a student would give to specific questions, to identify student misconceptions, and to plan the type of pedagogical instruction to be given to the student.

This paper describes an intelligent tutoring system (ITS), PRESTO, that has some of these capabilities. PRESTO can determine, from a student's description of qualitative relationships among physical properties, underlying misconceptions that the student has about how these physical properties govern a device. From the student's description, PRESTO constructs a representation of the student's mental image of the device. This gives the ITS the ability to reason the way the student reasons, to predict answers to specific questions, and to identify misconceptions. The ITS deals with misconceptions in three ways. First, it can present the student with a simpler device that clearly illustrates the misconception affecting the behaviour of the simpler device and then encourage analogy to the original device. PRESTO can also explain contradictory relationships by explicitly showing the student how these contradictions lead to impossible behaviour of the device. Finally, the system has been designed so that future versions of it will be able to simulate the device in operation, and thereby demonstrate to the student the effects of particular relationships among physical properties on the working device.

PRESTO uses qualitative reasoning in order to represent the student's mental model of the physical device under consideration. It has been shown that in the domain of physical systems, experts tend to reason in a qualitative as opposed to quantitative fashion [Brown 84], [Frederikson & White 88], [White 88], [White & Frederikson 88]. That is, an expert will examine how changes in the physical system propagate through the system via the qualitative relationships among the system's variables. If a problem requires a quantitative solution, it is developed only after the problem has been analysed and understood in qualitative terms [White 88]. It would seem that students learning the operation of a physical device would similarly use qualitative reasoning. Thus, it appears that the work done in qualitative reasoning could be useful in the development of a representation of deep student models in the domain of physical systems.

Background

In intelligent tutoring systems, it is useful to be able to model the student's knowledge in order to provide individualized instruction. Wenger [Wenger 87] states that instead of just being able to represent the target expertise and calculate a level of mastery for the student, a student model should be able to provide an explicit representation of the student's incorrect versions of the target expertise in order that remedial action may be taken. Self [Self 88] also points out that a student model should not have to provide value judgements on the correctness of the student's knowledge. The student modelling problem should be one of representing what a student believes. These beliefs should be represented in their own terms, not with respect to some target knowledge.

Most student models are shallow; they are not concerned with the deep "mental modelling" level at which students formulate their conceptions of the world around them. Mental models are used to organize people's conceptions and to be useful must predict behaviour with some degree of accuracy. Through interaction with the world, people continue to modify their mental models in order to better predict outcomes in the real world [Norman 83]. The research reported in this paper is concerned with how the mental model level of a student model can be represented and used for tutoring.

PRESTO is designed to determine and represent the student's mental model of a physical device. If the student's mental model is inaccurate, the student can be led to re-evaluate his or her mental model by being shown simpler devices, by having contradictions explained or by actually seeing anomalies in the behaviour of the device. Through this process of re-evaluation on the part of the student, PRESTO attempts to encourage the student to refine and/or correct his or her mental model of the device.

The mental modelling representation scheme is confluence theory [deKleer & Brown 81], [deKleer & Brown 83], [deKleer & Brown 85]. Confluence theory provides a method for qualitatively describing the behaviour of the components of a physical system It uses envisioning to construct a causal model of a physical device's operation. Envisioning is performed with knowledge of the behaviour of the components (described qualitatively using confluences) as well as how they are connected to form a composite device. The device can be qualitatively simulated and interesting events in the functioning of the device can be presented in their causal order.

This method of qualitative reasoning meets several of the requirements for student model representation. Both a qualitative device model and a model of the student's perception of the device should recognize inconsistent specification, that is, both kinds of models should recognize the problem of specifying different values for the same attribute in any state of the device. Both kinds of models should have correspondence, that is, they should be faithful to the actual behaviour of the device (or student conception of the device) under examination. As well, both must be robust in unusual situations. In addition, qualitative simulation provides a method for running the student model in order to predict students' responses and the consequences of students' beliefs.

Williams, Hollan and Stevens [Williams et al 83] have devised a representation of mental models based upon deKleer and Brown's qualitative physics. They consider a mental model to be a causal model developed through envisionment. Douglas and Liu [Douglas & Liu 89] have extended the ideas of confluence theory in order to create a tutoring system, Heart Works, which provides a constructive simulation of a device as well as providing qualitative causal explanations of the device's functioning. Their work has focused on generating pedagogical explanations of device behaviour as well as providing a constructive simulation of the device. Our work focuses on using confluences and envisionment in constructing runnable student models.

Confluence-Based Student Modelling

PRESTO makes use of deKleer and Brown's confluence-based qualitative reasoning to represent its model of the student. Relationships among the different variables that govern the student's beliefs about the behaviour of the physical device are represented as confluence equations. Since each relationship among the variables in a physical device can be represented in an equation, a model of the physical device can automatically be generated based upon the student's description of the interactions among the different variables. Many of the other qualitative reasoning systems such as Qualitative Process Theory [Forbus 85] and QSIM [Kuipers 86] do not have this one-to-one mapping between relationship and representation, and as a result knowledge must be handcrafted into complex process equations or well formed formulae.

PRESTO works in the following manner: In order to determine a student's misconceptions about a physical device, the system extracts from the student, beliefs about related variables underlying the operation of the physical device. First, a physical device, labelled with all the relevant variables, is presented to the student in a diagrammatic format. The diagram potentially limits the possible types of models that the student can have of the physical device, but this is unavoidable as the system and the student require a common frame of reference for discussing the device. The tutoring system asks the student to select related variables and to specify their causal relationships for a specific single state of the device. The tutoring system queries the student in causal terms because it has been found that students tend to think in terms of explicit and directed causal relationships [Forbus & Gentner 90]. Based on the student's descriptions of related variables, confluence equations are created. Figure 1 illustrates the environment for querying the student in PRESTO using deKleer's familiar pressure regulator as the physical device.

The relationships described by the student are encoded into confluence equations to represent beliefs about the relationships between the variables associated with the pressure regulator. Suppose, for example, that the student believed there was no relationship between flow and pressure and that a direct relationship existed between the pressure difference and the area of the valve opening. These misconceptions would be reflected in the responses given when PRESTO asks which variables are influenced by a change in the flow into the device or by a change in pressure difference. The latter relationship would be encoded as the confluence

$$\partial_{pressure\_difference} - \partial_{area\_valve\_opening} = 0$$

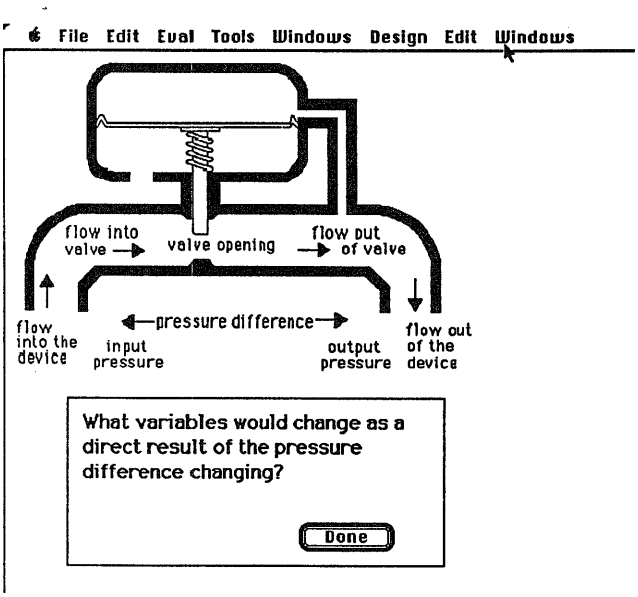

Figure 1. Querying the Student in PRESTO

After the student identifies all the variable relationships thought to be important, PRESTO has acquired a representation of the student's mental model of the pressure regulator. A typical representation is shown in Figure 2. It can be contrasted with the correct mental model of the pressure regulator as shown in Figure 3.

$$
\begin{aligned}
&\partial\text{pressure\_difference} - \partial\text{area\_valve\_opening} = 0\\
&\partial\text{pressure\_difference} + \partial\text{output\_pressure} = 0\\
&\partial\text{pressure\_difference} - \partial\text{input\_pressure} = 0\\
&\partial\text{flow\_into\_valve} - \partial\text{area\_valve\_opening} = 0\\
&\partial\text{area\_valve\_opening} - \partial\text{output\_pressure} = 0\\
&\partial\text{flow\_out\_of\_device} - \partial\text{flow\_out\_of\_valve} = 0\\
&\partial\text{flow\_into\_device} - \partial\text{flow\_into\_valve} = 0\\
&\partial\text{flow\_into\_valve} - \partial\text{flow\_out\_of\_valve} = 0
\end{aligned}
$$

Figure 2. Student's Faulty Mental Model

$$
\begin{aligned}
&\partial\text{pressure\_difference} - \partial\text{flow\_into\_valve}\\
&\qquad + \partial\text{area\_valve\_opening} = 0\\
&\partial\text{area\_valve\_opening} + \partial\text{output\_pressure} = 0\\
&\partial\text{pressure\_difference} + \partial\text{output\_pressure}\\
&\qquad - \partial\text{input\_pressure} = 0\\
&\partial\text{flow\_out\_of\_device} - \partial\text{flow\_out\_of\_valve} = 0\\
&\partial\text{flow\_into\_device} - \partial\text{flow\_into\_valve} = 0\\
&\partial\text{flow\_into\_valve} - \partial\text{flow\_out\_of\_valve} = 0\\
&\partial\text{flow\_out\_of\_device} - \partial\text{output\_pressure} = 0
\end{aligned}
$$

Figure 3. Correct Mental Model

In some cases, simple relationships between two variables of the physical device are not adequate. For example, variable A and B may be directly related, variable A and C may be inversely related. Thus A would be influenced by a combination of both B and C's effect. When two variables cause contradictory effects on a third variable, such as in a negative feedback loop, a three term confluence must be formed in order to eliminate contradictions.

In Figure 2, input pressure has a direct relationship with the pressure difference and the output pressure has an inverse relationship with the pressure difference. Thus the two confluences:

$$\partial\text{pressure\_difference} - \partial\text{input\_pressure} = 0 \quad \text{and}$$
$$\partial\text{pressure\_difference} + \partial\text{output\_pressure} = 0$$

collapse into the single confluence

$$\partial\text{pressure\_difference} + \partial\text{output\_pressure} - \partial\text{input\_pressure} = 0.$$

The confluence equations are run through a constraint satisfaction algorithm. During constraint satisfaction, misconceptions may be manifested as contradictions in the model or as missing or malformed confluences. In order to solve the constraints of the confluence equations, an initial variable is selected and some perturbation of the variable's value is introduced in order to induce a change in the device. The change is propagated through the confluences that comprise the student model. Equations with a single uninstantiated variable are solved first. When there are no equations with a single uninstantiated variables, two uninstantiated variables are solved. In this case one of the variables is given a value corresponding to the actual behaviour of the device and the propagation of values is continued. Propagation of values stops when all variables have a value, when all the equations have been used, or when all unused equations contain no instantiated variables. This indicates that the student has described the device with disjoint parts with one of the parts unaffected by the initial change. When the propagation of values is complete, the resulting values represent the behaviour of the device as it is conceived by the student.

Misconceptions are determined by comparing values of the variables determined by constraint propagation with values that represent actual behaviour of the device. If a value is in conflict with the actual value, then the confluence equation used to obtain that value is assumed to be a misconceived confluence. If all variables in a confluence are assigned values identical to the actual values, this does not indicate that there are no misconceptions. It is possible that during value propagation, not all confluence equations have been used. Thus, each confluence equation is tested with the generated values. If the equation is not valid for that set of values, then that confluence is deemed to be misconceived.

In the example, the student believed that the pressure difference and the area of the valve opening were directly related. This misconception is represented by the confluence equation:

$$\partial\text{pressure\_difference} - \partial\text{area\_valve\_opening} = 0.$$

When this equation is processed by the constraint satisfaction algorithm, it produces a behaviour inconsistent with the actual behaviour of the pressure regulator. Thus, the tutoring system focuses on this misconception and addresses it until it can convince the student that the relationship is inverse. When this happens the tutoring system is able to change the confluence to:

$$\partial \text{pressure\_difference} + \partial \text{area\_valve\_opening} = 0.$$

When a misconceived confluence is determined, it is first checked to see what kind of misconception it represents. A deviation from the actual behaviour of the pressure regulator could indicate that the student believes that a wrong relationship exists between the two variables of the confluence equation. However, if the confluence is one that would collapse into a multi-term confluence, it could indicate that some other confluence is missing.

In the example, the student believes that pressure and flow were not related. Thus the student incorrectly believes that the pressure difference across the valve has no relationship with the flow through the valve. As a result one of the confluences that represents the feedback loop of the pressure regulator is missing. In order to deal with this misconception, PRESTO presents the student with a simpler device to illustrate the behaviour that the missing confluence represented. This simpler device, a constricted pipe, is shown in Figure 4.

PRESTO asks the student to describe the behaviour of the constricted pipe. If the student understands that the pressure difference affects flow through the constriction, then the system leads the student by analogy to the pressure regulator. If the student does not understand the behaviour of the simpler device, the tutoring system will explicitly explain it. When tutoring on the misconception is complete, the student will believe that pressure difference is directly related to the flow into the valve and thus $\partial \text{Pressure\_difference} - \partial \text{flow\_into\_valve} = 0$ will be added to the student model. PRESTO will then collapse the three confluences representing the feedback loop of the valve:

$$\partial \text{Pressure\_difference} - \partial \text{flow\_into\_valve} = 0$$
$$\partial \text{Pressure\_difference} + \partial \text{area\_valve\_opening} = 0$$
$$\partial \text{flow\_into\_valve} - \partial \text{area\_valve\_opening} = 0$$

into a single confluence:

$$\partial \text{pressure\_difference} - \partial \text{flow\_into\_valve} + \partial \text{area\_valve\_opening} = 0$$

There are a number of misconceptions that the student may have which might not be identified through constraint satisfaction. These include missing confluences that may affect device behaviour but may not be detected because other confluences impose the necessary constraints on variables. Thus, if certain confluences are missing, simply simulating device behaviour may be insufficient. Therefore, all necessary confluences must exist in order for the student model to be deemed correct. Missing relationships also may subtly affect device behaviour, such as when missing confluences cause a variable to be unconstrained. This deviation in device behaviour would appear with the unconstrained variable not exhibiting any change when the device is simulated for the student. Another misconception that may not be determined from the constraint satisfaction occurs when the student believes that there are relationships among actually unrelated variables. These relationships may impose the proper constraints upon the variables within them; however, their existence indicates a misconception by the student about the physical properties governing the device.

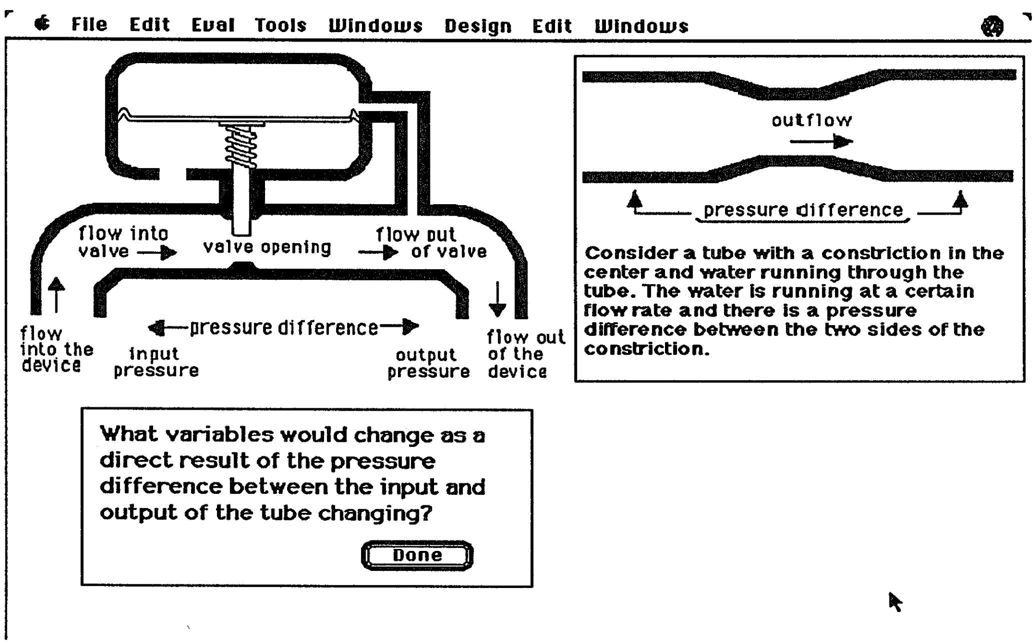

Figure 4. A Simpler Device for Removing a Misconception

In the example, the student initially states that pressure and flow are not related. As a result the student does not describe a relationship between the flow out of the device and the output pressure. Even though at this point all the variables can be constrained, it is a misconception on the part of the student not to describe how the load on the end of the pressure regulator offsets the relationship between the output pressure and flow. In order to deal with this misconception PRESTO again presents a simpler device to the student, in this case a pipe with a load on the end. When the student correctly describes the behaviour of the simpler device and correctly draws the analogy back to the pressure regulator, the following confluence will be placed in the student model:

$$\partial\text{Output\_pressure} - \partial\text{Flow\_out\_of\_device} = 0$$

The student model now is the same as the correct model of the pressure regulator and the tutoring system has successfully dealt with the misconceptions.

PRESTO deals with students' misconceptions in three ways. The first way is to present to the student an alternate, yet simpler physical device that will illustrate the behaviour in question. When the student sees how the variables interact in the simpler device, he or she should be able to make the analogy back to the original device. The second way of helping the student understand the misconception is to provide an explanation of the contradiction within the set of confluences which describe the device. PRESTO shows how the described relationships lead a variable to take on contradictory values. The final way of illustrating misconceptions to the student is through simulation. The student may describe relationships which do not lead to a contradiction, yet lead to incorrect behaviour of the device. This incorrect behaviour can be illustrated to the student by simulating the device as described. We have not yet implemented the simulation option.

By addressing misconceptions one by one, the tutoring system will help to evolve the student's mental model of the physical device to one which is correct. The end result is an intelligent tutoring system that supports students in refining their mental models of a physical device. It also supports the refinement of students' beliefs about the physical properties that govern the device. This corresponds to Self's idea [Self 88], that the purpose of a student model is to assist an intelligent tutoring system in provoking the student to consider the justifications and implications of his or her beliefs.

Conclusions

The student modelling capabilities of the confluence equations were tested by running twelve students through the implemented version of this tutoring system. From this testing a number of conclusions as to the capabilities as well as the limitations for this modelling scheme were discovered.

Qualitative differential equations worked well as a representational scheme in certain situations. In general, with this representation of the student's mental model, the tutoring system recognized most misconceptions about the underlying physics that governed the device's behaviour. The tutoring system was able to recognize deeper misconceptions, including the situation where the student correctly understands the physics that governs the device's behaviour but applies it incorrectly to the device or when the student is unable to envision the whole device's behaviour from the behaviour of its component parts. The tutoring system could also recognize misconceptions where the student did not understand the physics that governed the device's behaviour. In many cases, the students were surprised when PRESTO pointed out their misconceptions. PRESTO was able to eliminate some of the misconceptions of the students. Through interviews with the students after their sessions with PRESTO, it was found that they did learn something about the physics of the pressure regulator through their interactions with PRESTO. This shows that malformed confluence equations do in fact provide a direct indication of a misconception on the part of the student.

There are limitations to a student model representational scheme using confluence equations. A major limitation is the inability to explicitly represent causal relationships. Students tend to think in a causal manner. However, confluence equations contain only vague implicit notions of causality and thus there are types of misconceptions a confluence equation cannot represent For example, in the pressure regulator, a student could believe that an increase in the output pressure causes the valve to close. That belief would be correct. However, if the student believed that the closing of the valve caused a higher output pressure then that belief is incorrect. The problem is that both of these beliefs are represented by the same confluence equation. In both cases there is an inverse relationship between the variables. Consequently, PRESTO is unable to recognize all of the misconceptions that a student may possess. In order for confluence equations to become an adequate representational scheme, some improved method of representing causality must be added. PRESTO queries the students about causal relationships, but the causal information that the student supplies is simply discarded and only the information on variable relationships is maintained. By bringing causal information into the representation, the tutoring system would be better able to evaluate the student as well as to correctly recognize an additional class of misconceptions.

The interaction through which PRESTO constructs the preliminary mental model is not ideal. Many queries about individual relationships between pairs of variables are necessary, even for a device as simple as the pressure regulator. Better usage of inference and defaults dealing with the student's knowledge of basic confluences could improve the somewhat tedious query phase of PRESTO.

Confluence equations may not be perfect as a representation for a mental model, but they do have merit. In fact, much of the work done in the field of qualitative reasoning could have a major impact on student model representational schemes since many of the problems and issues in both fields are similar. By building upon representational schemes and reasoning approaches from the work in qualitative reasoning, student models can be greatly enhanced. Instead of simply representing a student's knowledge with respect to some target knowledge, a tutoring system should be able to represent a student's mental image of the tutoring domain. In doing this, the pedagogical aspects of the tutoring system can take advantage of knowing exactly how the student views the domain as well as being able to reason qualitatively like the student.

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