INTELLIGENT TUTORING SYSTEMS BASED UPON QUALITATIVE MODEL EVOLUTIONS

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ABSTRACT

One promising educational application of computers derives from their ability to dynamically simulate physical phenomena. Such systems permit students to explore, for instance, electrical circuit behavior or particle dynamics. In the past, these simulations have been based upon quantitative models. However, recent work in artificial intelligence has created techniques for basing such simulations on qualitative reasoning. Qualitative models not only simulate the phenomena of the domain, but also permit instructional systems to generate explanations of the behavior under study. Sequences of such models, that attempt to capture the progression from novice to expert reasoning, permit instructional systems to select problems and generate explanations that increase in complexity at an appropriate rate for each student. Since the acquisition of a qualitative understanding of the laws of physics and their implications is an important component of understanding physical phenomena, it is argued that systems based upon qualitative model progressions can play a valuable role in science education.

I INTRODUCTION

Our research has focused on (1) modelling possible evolutions in students' reasoning about electrical circuits as they come to understand more and more about circuit behavior, and on (2) using these model progressions as the basis for an intelligent learning environment that helps students learn (i) to predict and explain circuit behavior, and (ii) to troubleshoot by locating opens and shorts to ground in series–parallel circuits.

We have found that, even for the simplest circuit, there are different kinds of questions that you can ask about the behavior of the circuit that require different kinds of reasoning. For example, consider the elementary circuit illustrated in Figure 1, containing a battery, a switch, a light bulb, and a variable resistor. One could start by asking, "If I close the switch, will the light in this circuit be on or off?" This type of question can be answered by a simple form of qualitative reasoning, which we call "zero order" (because it employs no derivatives). Zero order models reason (1) about whether or not devices have voltages applied to them based upon the conductivity and resistance of other devices within the circuit, and (2) about how dramatic changes in conductivity, such as closing a switch, can affect the behavior of the circuit.

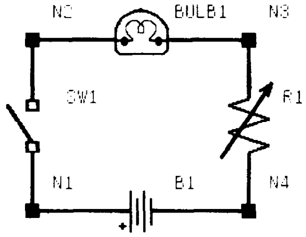


Figure 1.

One could go on to ask, "What happens to the light as I increase the resistance of the variable resistor? Does the light get brighter or dimmer?" Answering this type of question requires a more sophisticated form of qualitative reasoning, which we call "first order". First order models reason about how increasing the resistance in a branch of a circuit increases and decreases voltages within the circuit. The qualitative model is thus no longer simply reasoning about whether or not there is a voltage applied to a device, rather, it is determining whether the voltage is changing and is, therefore, utilizing qualitative derivatives. This type of analysis is crucial when analyzing, for instance, the occurrence of feedback within a circuit.

Finally one can ask still more precise questions about the behavior of the circuit shown in Figure 1. For example, one could ask, "When I close the switch, how bright will the light be?" To answer such a question requires a quantitative analysis of the circuit. Purely qualitative models are no longer sufficient to capture the reasoning necessary to answer this type of question.

We argue that in instruction, one should start by helping students to acquire a progression of increasingly sophisticated, zero order, qualitative models that enable students to reason about gross aspects of circuit behavior. This class of models can help students to develop basic circuit concepts such as resistance, conductivity, and voltage drop. It can also introduce students to fundamental circuit principles such as Kirchhoff's voltage law and help them to understand how changes in one part of the circuit can cause changes in other parts of the circuit. Once these fundamental aspects of circuit behavior have been mastered in qualitative terms, we argue that one should then introduce students to reasoning about more subtle aspects of circuit behavior by helping them to acquire first order, qualitative models of circuit behavior.

Finally, only after students can reason about and understand circuit behavior in qualitative terms, should quantitative reasoning be introduced. Further, the form of quantitative circuit analysis taught should be a logical extension of the qualitative reasoning that the students have already mastered.

This approach represents a radical departure from how physical theories are typically taught. Traditionally, only quantitative analysis is taught and students are left to develop their own qualitative methods, which they rarely do until long after they become experts at quantitative analysis (Larkin et al., 1980; Chi et al., 1981; Cohen et al., 1983).

In this paper, we will argue for the instructional necessity of starting with zero order, qualitative models. We will then go on to describe an instructional environment that we have implemented and tried out with high school students.

II AN OVERVIEW OF THE INSTRUCTIONAL SYSTEM

The learning environment lets students solve problems, hear explanations, and perform experiments, all in the context of interacting with a dynamic simulation of circuit behavior. However, unlike most simulations, the underlying model is qualitative not quantitative. Further, the simulation is performed not by a single model, but rather by the progression of zero order models that increases in sophistication in concordance with the evolution of the students' understanding of the domain. Learning thus is regarded as a process of model evolution: students attempt to formulate a series of models, each of which is adequate for solving some subset of problems within the domain.

Viewing instruction as producing in the student a progression of models permits a tutoring system architecture with elegant properties. Within our system, the student model, the tutor, and the domain simulation are incorporated within the single model that is active at any point in learning. This model is used to simulate the domain phenomena, is capable of generating explanations by articulating its behavior, and furnishes a desired model of the students' reasoning at that particular stage in learning. The progression of models also enables the system to select problems and generate explanations that are appropriate for the student at any point in the instructional sequence. In order to motivate students to transform their models into new models, they are given problems that the new model can handle but their present model cannot. This evolution of models also enables the system to focus its explanations on the difference between the present model and the new model.

Such a system architecture also permits a variety of pedagogical strategies to be explored within a single instructional system. Since the system can turn a problem into an example by solving it for the student, the students' learning can be motivated by problems or by examples. That is, students can be presented with problems and only see examples if they run into difficulty; alternatively, they can see examples first and then be given problems to solve. Also, by working within the simulation environment, students can use a circuit editor to construct their own problems and thus explore the domain in a more open ended fashion. The system is capable of generating runnable qualitative models for any circuit that the student or instructional designer might create. Further, the learning process can be managed either by the system or by the student. For example, students can be given a map of the problem space and can decide for themselves what class of problems to pursue next or even what pedagogical strategy they want to employ.

III THE INSTRUCTIONAL NEED FOR ZERO ORDER MODELS

The pioneering work of deKleer (1979) and others (in Bobrow (Ed.), 1985) has shown how models can be developed that enable a computer to reason qualitatively about a physical domain. Further, these researchers have demonstrated that such models can be adequate to solve a large class of problems (e.g., deKleer in Bobrow (Ed.), 1985). Our work on the design of qualitative models for instructional purposes has focused on creating models that (1) enable decompositions of sophisticated models into simpler models that can, nonetheless, accurately simulate the behavior of some class of circuits, and (2) enable the causality of circuit behaviors for the simpler models to be clear and at the same time compatible with that for more sophisticated models.

DeKleer (in Bobrow 1985, p. 208) argues that: "Most circuits are designed to deal with changing inputs or loads. For example, ... digital circuits must switch their internal states as applied signals change ... . The purpose of these kinds of circuits is best understood by examining how they respond to change." DeKleer's behavioral circuit model reasons in terms of qualitative derivatives obtained from qualitative versions of the constraint equations ("confluences") used in quantitative circuit analysis. These enable it to analyze the effects of changing inputs on circuit behavior.

The difficulty with utilizing such a model, at least at the initial stage of instruction, is that novices typically do not have a concept of voltage or resistance, let alone a conception of changes in voltages or resistance (Cohen et al., 1983; Collins, 1985; Steinberg, 1983). For example, as part of a trial of our instructional system, we interviewed seven high school students who had studied physics as part of a middle school science course, but who had not taken a high school physics course. They all initially exhibited serious misconceptions about circuit behaviors. For example, when asked to describe the behavior of the light in the circuit shown in Figure 2 as the switches are opened and closed, only one of the seven students had a concept of a circuit. The other students predicted that the bulb would light if only one of the switches were closed. A typical remark was the following, "If one of the switches on the left is closed, the light will light. It does not matter whether the switches on the right are open or closed." Further, they said, " if you close both switches on the left, the light will be twice as bright as if you close only one of them". In addition to this lack of a basic circuit concept, all seven of the students predicted that when you close the switch in Figure 3, the light would still light -- the statement that the switch was not resistive when closed did not matter. In fact, five of the students stated that they did not know what was meant by the term "not resistive". They thus had no conception of how a non-resistive path in a circuit could affect circuit behavior.

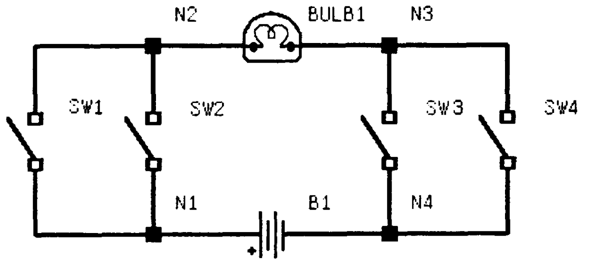
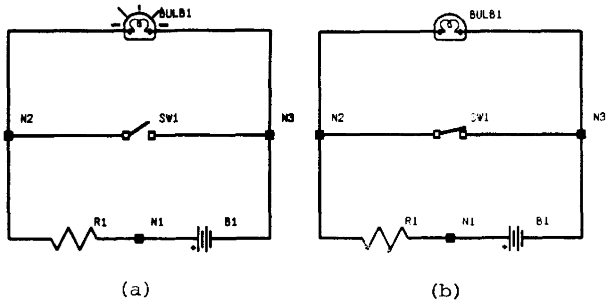


Figure 2.

Novices such as these, who do not have accurate models of when a voltage is applied to a device in a circuit, could not possibly understand what is meant by a change in voltage across a device. Thus, we argue that students should initially be taught a progression of zero order, qualitative models that reason about gross aspects of circuit behavior. This type of model can accurately simulate the behavior of a large class of circuits, and can be utilized to introduce fundamental ideas about circuit behavior.



(a) (b)

Figure 3.

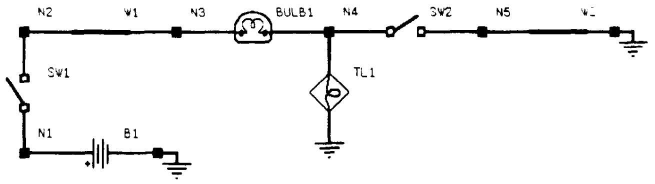


Figure 4.

The knowledge embedded in the zero order models has been shown to be the type of knowledge that even college physics students lack (Cohen et al., 1983), and is also crucial knowledge for successful troubleshooting. For example, consider an elementary form of troubleshooting such as trying to locate an open in the circuit shown in Figure 4. Imagine that a test light is inserted into the middle of the circuit as shown in the figure. In order to make an inference about whether the open is in the part of the circuit in series with the test light or the part in parallel with it, one needs to know that if switch #1 were open, the light would not be on even if the circuit had no fault. Similarly, one needs to understand that if switch #2 were closed, the test light would not be on even if the circuit were unfaulted. Thus, even for performing the most elementary type of electrical troubleshooting, one needs a "zero order understanding" of circuit behavior.

IV THE ZERO ORDER MODELS

The zero order models incorporate knowledge of the structure of the circuit, the behavior of the devices within the circuit, and basic electrical principles relating to the distribution of voltages within the circuit. The instructional system also includes a progression of general troubleshooting algorithms for localizing faults within a circuit (see, White & Frederiksen, 1984; White & Frederiksen, 1985). These algorithms utilize the behavioral models as part of their problem solving process. Both the behavioral models and troubleshooting algorithms can articulate their thinking, both visually and verbally, when simulating the behavior of a given circuit or when troubleshooting.

A. Device Models

The behavioral models contain device models for devices typically found in circuits. The devices modelled are batteries, switches, resistors, bulbs, diodes, fuses, capacitors, transistors, test lights, and wires (wires are explicitly introduced as devices). Device models include rules for determining a device's state, based upon the circuit environment of the device. For example, if there is a voltage drop across the two ports of a light bulb, the light bulb will be in the "on" state; otherwise it is in the "off" state. When a device's state changes, the device model activates additional rules which reevaluate a set of variables associated with the device. These variables include (1) the conductivity of the device (is it purely conductive, conductive but resistive, or nonconductive), and (2) whether or not the device is a source of voltage. For example, when a capacitor is in the charged state, it is nonconductive and a source of voltage. Finally, the device models include fault states, which include rules for altering the device variables to make them consistent with a particular fault, and which override the normal states for the device. For example, when a light bulb is faulted "open", it becomes non-conductive and its state will be "off".

When a particular device, such as a light bulb, is employed within a particular circuit, a data table is created for the specific instantiation of that device in that circuit. This table is used to record (1) the present state of the device, (2) whether it is presently a voltage source, (3) its internal conductivity (what possible internal conductive paths exist among its ports and whether they are presently purely conductive, resistive, or nonconductive), (4) the device polarity, as well as (5) its connections to other devices in the circuit, and (6) its fault status. When the student is performing a mental simulation of a particular circuit, the student must also keep track of this information.

A mental model for a device enables the student to determine the state of the device regardless of the circuit environment in which it is placed. Information related to the state of the device, such as its internal conductivity and whether or not it is a source of voltage, will in turn affect the behavior of other devices in the circuit. Such a device model will thus form the basis for understanding the causality of circuit behavior in terms of showing how a change in state of one device can produce a change in state of another device within the circuit.

B. Circuit Principles

When simulating a particular circuit, the only information that the qualitative simulation requires is information about the structure of the circuit, that is, the devices and their interconnections. All of the information about circuit behavior, as represented by a sequence of changes in device states, is inferred by the qualitative simulation as it reasons about the circuit. To reason about device polarity and state, the device models utilize general qualitative methods for circuit analysis. For instance, when attempting to evaluate their states, device models can call upon procedures to establish voltages within the circuit. In the case of the zero order models, these procedures determine, based upon the circuit topology and the states of devices, whether or not a device has a voltage applied to it.*

The most sophisticated zero order voltage rule is based on the concept that, for a device to have a voltage applied to it, it must occur in a circuit (loop) containing a voltage source and must not have any non-resistive paths in parallel with it within that circuit. More formally, the zero order voltage rule can be stated as: If there is at least one conductive path to the negative side of a voltage source from one port of the device (a return path), and if there is a conductive path from another port of the device to the positive side of that voltage source (a feed path), with no non-resistive path branching from any point on that "feed" path to any point on any "return" path, then, the device has a voltage applied to that pair of ports.**

Changes in a circuit, such as closing a switch, can alter in a dramatic way, the conductivity of the circuit and thereby produce changes in whether or not a device has a voltage applied to it. To illustrate, when the switch is open in the circuit shown in Figure 3(a), the device model for the light bulb calls upon procedures for evaluating voltages in order to determine whether the light's state is on or off. The procedure finds a good feed path and a good return path and thus the light bulb will be on. When the switch is closed, as shown in Figure 3(b), the procedure finds a short from the feed to the return path and thus the light bulb will be off.***

C. Causal Explanations

Simply having the model articulate that when the switch is closed, the light will be off because there is a non-resitive path across it, is not a sufficient causal explanation for students who have no understanding of (1) what is meant by non-resistive, or (2) what affect such a path can have on circuit behavior. First of all, students need definitions for concepts such as voltage, resistance, current, device state, internal conductivity, series circuit, and parallel circuit. Further, they need a "deeper" causal explanation of the circuit's behavior. For instance, there are two alternate perspectives on the causality of circuit behavior -- a current flow perspective and a voltage drop perspective. To illustrate, the following are explanations that (1) a current flow model, and (2) a voltage drop model could give as to why the light is off when the switch is closed for the circuit shown in Figure 3.

The current flow model could state: "In order for the bulb to light, current must flow through it. There is a device in parallel with the bulb, the switch. In parallel paths, the current is divided among the paths. More current flows through the path with the least resistance. If one of the paths has no resistance, all of the current will flow through it. Since the bulb has resistance and the switch does not, all of the current will flow through the switch. Since there is no current flow through the bulb, it will be off."

Whereas, the voltage drop model could state: "In order for the bulb to light, there must be a voltage drop across it. There is a device in parallel with the bulb, the switch. Two devices in parallel have the same voltage drop across them. Voltage drop is directly proportional to resistance: If there is no resistance, there can be no voltage drop. Since the switch has no resistance, there is no voltage drop across the switch. Thus, there is no voltage drop across the light, so the light will be off."

One could be given even "deeper" accounts of the physics underlying circuit causality. For instance, the system could present physical models that attempt to explain why current flow and voltage drop are affected by resistance in terms of electrical fields and their propagation. However, for our present purposes, the system presents a causal account to the depth illustrated by the preceding models.

In explaining the behavior of the light in the preceding example, one could utilize either the voltage

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[*] In the case of the first order models, these procedures reason about whether the voltage drop across a device is increasing or decreasing as a result of changes in its resistance and the resistance of other devices in the circuit.

[**] By "voltage applied to a device", we mean the qualitative version of the open circuit (or Thevenin) voltage, that is, the voltage the device sees as it looks into the circuit. In the case of the zero order voltage rule, this is simply the presence or absence of voltage.

[***] The voltage procedures utilize topological search processes that are needed, for example, to determine whether a device has a conductive path to a source of voltage. The search processes utilize the information maintained by the device data tables concerning their circuit connections, polarity, internal conductivity, and whether or not they serve as voltage sources. Polarities are assigned to the ports of each device in the circuit by a general, qualitative, circuit orientation algorithm.

drop explanation or the current flow explanation, or both. Our view is that giving students both types of explanations, at least in the initial stages of learning about circuits, would be unnecessary and confusing. It would require students to construct two models for circuit behavior, and this would create a potential for them to become confused about circuit causality. However, later on students may learn to reason in either way about circuit behavior.

We therefore selected only one of the causal models. We chose the voltage drop explanation because current flows as a result of an electromotive force being applied to a circuit; because troubleshooting tasks typically are based upon reasoning about voltages and testing for them; and because research has shown that this is an important way of conceptualizing circuit behavior that even sophisticated students lack, as illustrated by the following quotation: "Current is the primary concept used by students, whereas potential difference is regarded as a **consequence** of current flow, and not as its **cause**. Consequently students often use V=IR incorrectly. A battery is regarded as a source of constant current. The concepts of emf and internal resistance are not well understood. Students have difficulties in analyzing the effect which a change in one component has on the rest of the circuit" (Cohen, Eylon, and Ganiel, 1983).

In addition, reasoning about how circuits divide voltage is a major component of our first order models. These models reason about changes in resistances and voltages within a circuit, using a qualitative form of Kirchhoff's voltage law. Thus getting students to reason in terms of voltages is compatible with the type of reasoning that will be required later on in the evolution of the students' models.

D. Control Structure

The simulation of circuit operation is driven by changes in the states of the devices in the circuit. These changes are produced by (1) changes in states of other devices, such as a battery becoming discharged causing a light to go out; (2) external interventions, such as a person closing a switch, or a fault being introduced into the circuit; and (3) increments in time, such as a capacitor becoming discharged. Whenever a device changes state, its status as a voltage source is redetermined by the device model, along with its internal conductivity/resistance. Whenever any device's internal conductivity or status as a voltage source changes, then time stops incrementing within the simulation and all of the other devices in the circuit reevaluate their states. This allows any changes in conductivity or presence of voltage sources within the circuit to propagate their effects to the states of other devices. The circuit information used for this reevaluation is the set of device data tables existing at the initiation of the reevaluation (not those that are being created in the current reevaluation cycle). This is to avoid unwanted sequential dependencies in determining device states. If in the course of this reevaluation some additional devices change state, then the reevaluation process is repeated. This series of propagation cycles continues until the behavior of the circuit stabilizes and no further changes in device states have occurred. Time is then allowed to increment and the simulation continues. When any further changes in device internal conductivity or status as a voltage source occur, due either to the passage of time or to external intervention, time is again frozen and the propagation of state changes is allowed to commence once again.

E. A Sample Zero Order Circuit Simulation

As an illustration of how a zero order model reasons, consider a simulation of the behavior of the circuit illustrated in Figure 5.

Initially suppose that both switches are open, the light bulb is off, and the capacitor is discharged. Then, suppose that someone closes switch #1. This change in the internal conductivity of a device causes the other devices in the circuit to reevaluate their states. The capacitor remains discharged because switch #2 being open prevents it from having a good return path. The light bulb has good feed and return paths, so its state becomes on. Since, in the course of this reevaluation no device changed its conductivity, the reevaluation process terminates. Note that even though the light bulb changed state, its internal conductity is always the same, so its change of state can have no effect on circuit behavior and thus does not trigger the reevaluation process.

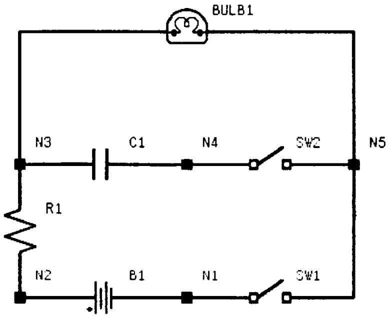

Figure 5.

Now, imagine that someone closes switch #2. This change in state produces a change in the conductity of the switch and triggers the reevaluation process. The light bulb attempts to reevaluate its state and finds that its feed path is shorted out by the capacitor (which is purely-conductive because it is in the discharged state) and switch #2 (which is also purely-conductive because its state is closed), so its state becomes off. The capacitor attempts to reevaluate its state and finds that it has a good feed and return path, so its state becomes charged. This change in state causes it to reevaluate its internal conductivity, and to reevaluate whether it is a source of voltage. As a result of the capacitor becoming charged, it becomes non-conductive, and a source of voltage. This change in the internal conductivity of the capacitor causes the reevaluation process to trigger again. The light bulb reevaluates its state and finds that it has a good feed and return path (it is no longer shorted out by the capacitor because the capacitor is now charged and therefore non-conductive) and its state becomes on. This change in the light bulb's state has no effect on the light bulb's internal conductivity so the reevaluation process terminates.

Suppose that someone then opens switch #1. This changes the switches internal conductivity and therefore causes all other devices to reevaluate their states. The light bulb no longer has a good return path with respect to the battery. However, it has a good feed and return path to another source of voltage within the circuit, the capacitor (which is charged and therefore a source of voltage). The state of the light bulb will thus be on. The capacitor no longer has a good return path to a source of voltage and it has a conductive path across it, so its state becomes discharged and it becomes purely-conductive and is not a source of voltage. This change in the capacitors internal conductivity causes the light bulb to reevaluate its state. Since the capacitor is no longer a source of voltage, and since switch #1 is open thereby preventing a good return path to the battery, the light bulb concludes that its state is off. This change in state has no effect on the light bulb's internal conductivity so the reevaluation process terminates.

Notice that this relatively unsophisticated qualitative simulation has been able to simulate and explain some important aspects of this circuit's behavior. It demonstrates how when switch #2 is closed, it initially shorts out the bulb, and then, when the capacitor charges, it no longer shorts out the bulb. Further, it explains how when switch #1 is opened, the capacitor causes the light bulb to light initially, and then, when the capacitor becomes discharged, the light bulb goes out.

One of the most impressive features of the type of qualitative, causal model described in this paper is its utility in helping to solve a wide range of circuit problems. For example, the student can be asked to predict the state of a single device after a switch is closed, or to describe the behavior of the entire circuit as various switches are opened and closed, or to determine what faults are possible given the behavior of the circuit. Further, students can be asked to locate a faulty switch within a circuit, or to design a circuit such that when the switch is closed, the light in the circuit will be off. Performing this type of mental simulation of circuit behavior is instrumental in solving all of these types of problems.

V MODEL TRANSFORMATIONS

The learning environment is not based upon a single, zero order, qualitative model, but rather, it is based upon a progression of increasingly sophisticated models that correspond to a possible evolution of a learner's model. The system can help students to transform their model by presenting to them those problems that can be solved by the transformed model but not by the untransformed model. The students will thus be motivated to revise their existing qualitative model in an appropriate direction.

For example, the learning environment can help students who have a rudimentary conception of voltage drop to refine their conception by learning about the effects of non-resistive paths. This particular model transformation can be motivated by giving students problems where they have to predict, for instance, the behavior of the light bulb in the circuit shown in Figure 3 as the switch is opened and closed.

In order to facilitate such a transformation, the system can turn any problem into an example for the student by reasoning out loud while it solves the problem. As models become more sophisticated, they also become more verbose. The mechanism for pruning explanations is to focus the explanations on the difference between the transformed and the untransformed model. Reasoning of the transformed model that was present in the untransformed model either does not articulate itself or, if it is necessary to support the model increment, is presented in summary fashion.

Looking at the difference between the transformed model and the student's current model also helps to define what aspects of the problem solving process should be represented to the student. For instance, if students are learning about determining when there is or is not a voltage drop across a device, the system illustrates paths to voltage sources. However, later in the model progression, when it is assumed that students already know how to determine the presence of a voltage drop, the paths are no longer displayed.

VI LEARNING STRATEGIES

The learning environment thus consists of an interactive simulation driven by qualitative models. Further, the progression of models defines classes of problems and facilitates explanation generation. This architecture for an intelligent tutoring system permits great flexibility in the students' choice of an instructional strategy.

Open-ended exploration. Students can construct circuits, explore their behavior (by changing the states of devices, inserting faults, and adding or deleting components), and request explanations for the observed behaviors. Students can thus create their own problems and experiment with circuits. The system thereby permits an open-ended exploratory learning strategy.

Problem-driven learning. In addition, the progression of models enables the system to present students with a sequence of problem solving situations that motivate the need for developing particular transformations of their models of circuit behavior. In solving new problems, the students attempt to transform their models of circuit behavior in concordance with the evolution of the system's models. The focus is on having students solve problems on their own, without providing them first with explanations for how to solve them. Only when they run into difficulty, do they request explanations of circuit behavior.

Example-driven learning. Alternatively, students can be presented with tutorial demonstrations for solving example problems by simply asking the system to reason out loud about a given circuit using its present, qualitative, causal model. Students can thus hear explanations of how to solve each type of problem in the series, followed by opportunities to solve similar problems. Since the focus is on presenting examples together with explanations prior to practice in problem solving, we term this learning strategy "example-driven".

Student directed learning. The classification of problems created by the progression of models provides facilities students can use in pursuing instructional goals of their own choosing. Problem sets are classified on the basis of the concepts and laws required for their solution, and on the instructional purpose served by the problem set. This enables students to pursue goals such as acquiring a new concept or generalizing a concept. The students can thus make their own decisions about what problems to solve and even about what learning strategy to employ.

The system has been tried out with seven high school students. Students were allowed to pursue their own learning strategies with the constraint that use of the circuit editor was restricted to the modification of circuits in the problem sets. Initially, all of the students exhibited serious misconceptions about circuit behavior, and lacked key electrical concepts. Further, none of them had any experience with troubleshooting. After five hours of working with the system on an individual basis, they were all able to make accurate zero order predictions about circuit behavior and could troubleshoot for opens and shorts to ground in series circuits. We found that differences between the students' mental models and those that we were trying to teach were not due to the inevitability of misconceptions, but rather, were due to limitations of the learning environment -- a non-optimality in either the form of the knowledge we were trying to impart, or the progression of models, or the type of problem selected to induce a particular model transformation. Thus our future research will focus on developing further the theory underlying model forms, model transformations, and instructional strategies. Also, we intend to to expand the set of instructional modes and problem types, by, for example, allowing students to design and troubleshoot, not only circuits, but also, the qualitative models that perform the circuit simulations.

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