Modeling Expertise in Troubleshooting and Reasoning About Simple Electric Circuits

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Working within the framework of designing a computer-based system for teaching automotive electrical troubleshooting, we are developing a model of expert troubleshooting and a qualitative causal model of circuit behavior. The purpose of these models is to demonstrate to students the troubleshooting process and to explain the operation of circuits in faulted and unfaulted conditions. Our instructional interest is in determining how models of circuit behavior influence the learning of troubleshooting and how training in troubleshooting influences learning to reason about circuits. In this paper we will focus on the psychological criteria for constructing models of troubleshooting and reasoning about circuits.

In modeling the troubleshooting process, we interviewed and observed expert mechanics, studied automotive manuals, and reviewed computer based troubleshooting systems (Forbus & Stevens, 1981; Rouse & Ruston, 1982; Sleeman & Brown, 1982). We have observed three broad categories of troubleshooting behavior: (1) symptom fault associations (Rasmussen & Jensen, 1974), (2) decision trees, and (3) knowledge based inferencing strategies. Training based upon symptom fault associations requires higher fidelity than is possible using computer simulations and requires many years to gain experience with low probability faults in the real world. Decision trees have the drawback of being difficult to remember, incomplete, and do not develop skills that would enable the learner to troubleshoot systems other than the one explicitly trained. Our goal, therefore, was to find a knowledge based inferencing strategy that would be flexible, transferable, and not too difficult to learn.

We have worked with an expert troubleshooter who utilizes and teaches a knowledge based strategy (the Feed-Device-Ground or FDG strategy) to students in a technical high school. The strategy appears to have general applicability and has several properties that make it easy to execute.

Firstly, the FDG strategy minimizes the number of entities about which one has to reason at any moment by focusing on one device at a time and dividing the circuit into three parts: feed, device, and ground (see Figure 1). The feed, for example, consists of all circuit elements between the positive voltage source and the device of focus. The ground is analogously defined. All inferences are made with reference to these three entities.

Secondly, the strategy seeks to eliminate ambiguities about the location of the fault before shifting the focus to another device. For instance, suppose that a test light (or voltmeter) is connected between the device and the negative terminal of the battery and that it does not light (or indicate a voltage). There are multiple faults that are consistent with this result: There could be an open or a short to ground in the feed to the device, the device itself could be faulty, or the ground circuit could be shorted. Given the ambiguity of such a test result, our expert has several techniques for determining whether the fault is in the feed, device, or ground system. One technique is to detach a possibly faulty ground system from the device. If the ground were shorted this detachment would cause the light to come on. Another technique is to provide a substitute feed to the device. If the light were then to come on, one could infer that there is a fault in the feed system. A further technique is to detach the feed system, while leaving the substitute feed in place. Then if the light were to come on, one could infer that the feed is shorted. If all of these techniques have been employed and the light still does not come on, one could then conclude that the device itself has an open or a short to ground. Using these methods, the fault can be isolated to be within the feed, device, or ground portion of the circuit.

Thirdly, the FDG strategy minimizes the memory demands for keeping track of what parts of the circuit are known to be good. Once the section of the circuit with the fault has been determined, the strategy involves serially searching that section of the circuit known to contain a fault (either the feed or ground) moving in a direction away from the device. This is done by repeatedly shifting the focus to the next device in the feed (or ground) system and utilizing the techniques for resolving ambiguity outlined above to constrain further the location of the fault. It should be noted that a serial search is not the most efficient procedure for large circuits; however, it does make it easy to remember what parts of the circuit have already been tested and found to be free of faults. This makes the FDG strategy easier to execute than strategies which utilize potentially more efficient search procedures, such as repeatedly shifting the device focus to the middle of the suspect part of the circuit.

The FDG strategy has the advantage of being generally applicable to simple electrical circuits and minimizes memory requirements for executing it. However, it does presuppose knowledge of electrical circuits and appears to require an ability to reason qualitatively about circuits. This may make it a difficult troubleshooting technique for a novice to master. For example, a student needs to understand that for current to flow through a device, there must be a continuous path from a voltage source to the device and back to the opposite terminal of the voltage source. The implication of this principle is that in a series circuit an open will prevent current from flowing. However, in a parallel circuit, an open will not necessarily prevent current from flowing through the device if there is an alternative path for the current to take. Furthermore, students need to understand that in the case of parallel circuits, more current will flow in the path of lower resistance and that if there is one path with no resistance, all of the current will follow that path. The important implication of this principle for troubleshooting is that shorts to ground provide alternative paths with negligible resistance and thereby prevent current from flowing through the remainder of the circuit.

Given the need to teach these electrical principles and their implications as a prerequisite to teaching the FDG strategy for troubleshooting, we are creating an instructional environment that is capable of demonstrating and providing practice in using these principles. The basis of this system is a qualitative causal model that simulates the operation of an electrical circuit in both unfaulted and faulted states. The qualitative causal model incorporates knowledge of the structure of the circuit, the functioning of the devices within the circuit, and the electrical principles presented above.

There are a number of instructional requirements that constrain the form of this qualitative causal model. Firstly, the model is to be capable of supporting graphical representations of circuit operation. These representations illustrate circuit topology, states of devices (e.g., an open or closed switch, a coil with a field around it), and current flow. They can show, for simple circuits, the effects of faults such as opens and shorts to ground on current flow and on test light behavior. Secondly, the model is to provide a simulation environment within which the FDG "expert" program can demonstrate troubleshooting concepts and procedures and the student can practice execution of the strategy. Faults can be introduced without the student's awareness, and the student has facilities for inserting a test light, setting the positions of switches and points, establishing a device of focus, installing substitute feeds, and detaching feed and ground circuits. The system will faithfully reproduce the effects of these manipulations on the behavior of the test light and the operation of the circuit. Thirdly, the model is to be capable of generating explanations of circuit operation. Moreover, these explanations employ the same qualitative reasoning principles used in the execution of the FDG strategy. When a component is set to be faulty, the system describes the effects of the fault on the operation of other components, on the behavior of a test light inserted into the circuit, and on the functioning of the ignition circuit as a whole.

In order to meet these instructional requirements, the model consists of (1) a representation of circuit topology, (2) a functional model for each device within the circuit, (3) rules for evaluating device states at each point in time, and (4) procedures for tracing the circuit to aid in evaluating conditions for device states. The topological representation describes the connections between devices within the circuit. The functional model for a device specifies its operating states and the conditions for entering those states. For example, the coil has two states: field building and field dissipating. The condition for entering the field building state is that an electrical potential exists across the Primary-Plus and Primary-Minus terminals. The condition for the field dissipating state is that there is no such electrical potential. In order to determine if an electrical potential exists, the model must check for a continuous path from each terminal to a voltage source. To determine if the path is continuous, the model must check the states of each device to see if it provides a conductive path.

If a break in the circuits occurs (if a switch is open or a device is faulted open), alternative parallel paths are searched. If no continuous path is found, the model concludes that there is no operating voltage for the coil. On the other hand, if at least one continuous path is found for both the feed and ground systems, then the model checks for shorts (paths of negligible resistance to the opposite side of the voltage source). In this way, characteristics of the circuit are examined in order to evaluate the operating requirements for a device. An advantage of this model is that the effects of faults on the operation of the circuit are easily determined. A further advantage is that the circuit tracing procedures are similar to those employed by the FDG strategy. Thus, in a sense, the troubleshooting strategy and the qualitative causal model utilize a similar kind of reasoning.

The model runs in discrete steps in time. All devices evaluate their states in parallel and appropriate changes in the graphic display are made. If explanations are desired, each step in the reasoning process can be articulated. The model also supports student initiated tests. When a test light is positioned in the circuit, procedures analogous to those described above deduce the state of the light. Running the model also enables one to determine the set of faults consistent with a given test result.

This model is similar to that of de Kleer and Brown (1983) in that it is based on qualitative causal reasoning. We selected this class of model (see also Kuipers, 1982) because it enables the instructional system to generate causal explanations that may help students to understand circuit behavior. Since our focus is on troubleshooting rather than "envisioning", our model differs from that of de Kleer and Brown in several respects. We sought a model that would be robust in permitting faults to be introduced without requiring a new model for each perturbation in the circuit. By utilizing context free functional models for devices along with a topological search process for evaluating device conditions, we were able to construct a single model that accounts for the effects of faults on the operation of the circuit.

Instructional considerations led us to decompose this domain into a troubleshooting component (the FDG strategy) and a circuit reasoning component (the qualitative causal model). This decomposition allows us to consider the effects of teaching reasoning about circuits on the learning of troubleshooting skills and the effects of teaching troubleshooting on learning to reason about circuits. This latter case is interesting from the standpoint of helping students understand basic circuit theory since the troubleshooting task is a form of qualitative problem solving that can motivate the learning of circuit principles.

References

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Figure 1.

Division of a circuit into feed, device, and ground circuit elements.