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AUTHOR Feurzeig, Wallace; And Others
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ABSTRACT

The scientific and technical publications summarized in this report describe research on intelligent instructional systems sponsored by the Personnel and Training Research Programs, Psychological Sciences Division, of the Office of Naval Research. Abstracts of the following papers are presented: (1) "Understanding Reflective Problem Solving" (W. Feurzeig and F. Ritter); (2) "Intelligent Tutors as Intelligent Testers" (J. R. Frederiksen and B. Y. White); (3) "Qualitative Models and Intelligent Learning Environments" (B. Y. White and J. R. Frederiksen); (4) "Developing an Exportable ICAI [Intelligent Computer-Assisted Instruction] Technology" (W. Feurzeig); (5) "OREO--Adding Orientation to a Dynamic Qualitative Simulation" (F. Ritter); (6) "Intelligent Tutoring Systems Based upon Qualitative Model Evolutions" (B. Y. White and J. R. Frederiksen); (7) "Progressions of Qualitative Models as a Foundation for Intelligent Learning Environments" (B. Y. White and J. R. Frederiksen); (8) "AI [Artificial Intelligence] Aids for Design and Automation of CAI Programs" (W. Feurzeig); (9) "Cognitive Science, Artificial Intelligence and Complex Training" (W. Feurzeig); (10) "A System for Teaching a Qualitative Understanding of Electrical Circuit Behavior and Troubleshooting" (J. R. Frederiksen and B. Y. White); (11) "QUEST: Qualitative Understanding of Electrical System Troubleshooting" (B. Y. White and J. R. Frederiksen); (12) "Designing an Expert system for Training Automotive Electrical Troubleshooting" (W. Feurzeig, J. Frederiksen, B. White, and P. Horwitz); and (13) "Modeling Expertise in Troubleshooting and Reasoning about Simple Electric Circuits" (B. Y. White and J. R. Frederiksen). Nine oral presentations on the research are also listed. (MES)

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Intelligent Instructional Systems for Teaching Procedural Skills

Final Report

Wallace Feurzeig, John R. Frederiksen, and Barbara Y. White

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Final Report

February 10, 1987

INTELLIGENT INSTRUCTIONAL SYSTEMS FOR TEACHING PROCEDURAL SKILLS

Wallace Feurzeig
John R. Frederiksen
Barbara Y. White

The research summarized in this report was sponsored by the Personnel and Training Research Programs, Psychological Sciences Division, Office of Naval Research under Contract No. N0014-82-C-0580, Contract Authority Identification Number, NR 154-493.

ABSTRACT

This Final Report summarizes the scientific and technical publications and lists the oral presentations describing the research carried out under this contract.

Intelligent Instructional Systems for Teaching Procedural Skills

PUBLICATIONS

Feurzeig, W., and Ritter, F. (1987) "Understanding Reflective Problem Solving". In Intelligent Tutoring Systems: Lessons Learned, ed. Psotka, J., Massey, D., Mutter, S., Lawrence Erlbaum Associates, Hillsdale, N. J.

Abstract

ICAI systems typically acquire knowledge about a student's misconceptions and procedural bugs by making inferences based on the student's problem-solving actions. Thus, in work on electronic circuit troubleshooting problems, the student's knowledge and difficulties are inferred from observations of the tests and measurements he makes along the way. In this paper we propose the alternate strategy of acquiring information directly from the student. This strategy has been implemented as an instructional monitor within the QUEST system for training electrical system troubleshooting. Every time the student calls on the QUEST simulator to carry out a test or make a circuit measurement, the monitor asks the student the reason for his action. After the simulator performs the requested action, the monitor asks the student what he learned from the test or measurement. Student responses are made by selecting items in response windows and pointing at circuit components or subcircuits. The approach can yield extensive information about the student's expectations, theories, and plans as a foundation for making inferences about his misconceptions and bugs. This strategy is therefore proposed as a valuable complement to pure inferencing methods. The detailed operation of the monitor is described and the transcript of a QUEST troubleshooting interaction under this mode of operation is shown.

Frederiksen, J.R. & White, B.Y. (1987) "Intelligent Tutors as Intelligent Testers". In Diagnostic Monitoring of Skill and Knowledge Acquisition. Frederiksen, N., Glaser, R., Lesgold, A., & Shafto, M. (Editors), Lawrence Erlbaum Associates, Hillsdale, New Jersey.

Abstract

This paper explores the use of intelligent tutoring systems in the assessment of students' knowledge bases, problem solving processes, and learning strategies. We describe a form of tutoring system that is based upon a progression of cognitive models that reason and solve problems within a domain. Such model progressions can provide runnable simulations of students' mental models, which can be used to determine not only what problems a student is capable of solving at a given point in training, but also what additional concepts and skills a student must acquire in order to solve problems that he or she currently cannot solve. Since tutoring systems of this class can support different learning strategies, it also becomes possible to determine the student's preferred mode of learning, or to assess his or her rate of

learning when a particular learning strategy is imposed on the student. Using such measures derived within the tutoring environment, it should be possible to predict learning outcomes not only within the tutoring system, but also in other learning environments and on the job.

White, B.Y. & Frederiksen, J.R. (1987) "Qualitative Models and Intelligent Learning Environments". In AI and Education. Lawler, R. & Yazdani, M. (Editors). Ablex Publishing Corporation, Norwood, New Jersey.

Abstract

One promising educational application of computers derives from their ability to dynamically simulate physical phenomena. Such microworlds 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 microworlds on qualitative reasoning. Qualitative models not only simulate the phenomena of the domain, but also can generate explanations for the behavior under study. Sequences of such models, that attempt to capture a progression from novice to expert reasoning, permit microworlds to incorporate features of intelligent tutoring systems. The learning environment can embody the model progression by making available to students (1) microworlds of increasing complexity, (2) problems classified by the level of model required for their correct solution, and (3) explanations focused on the differences between models and their predecessors. Students can then utilize these microworlds, problem sets, and explanations to aid them in developing an understanding of the domain.

Feurzeig, W. (1986) "Developing an Exportable ICAI Technology". In the Proceedings of the Workshop on Introducing Intelligent Computer Assisted Instruction into Military Training, U.C.L.A., Los Angeles, CA., U. S. Army Research Institute Technical Report, Arlington. VA.

Abstract

The instructional capabilities of current ICAI systems and the inherent difficulties in making intelligent inferences about a student's knowledge and underlying misconceptions, as illustrated by the student modeling work in systems such as WEST and DEBUGGY, are summarized. The teaching of qualitative thinking and the use of qualitative simulation models for producing understandable explanations, in systems such as Steamer and QUEST, which support student exploration of system behavior and student practice in system operation and troubleshooting, is described. The paper calls for the development of versatile training systems that integrate facilities for student-directed exploration and practice with tutorial ICAI programs. These systems would be designed to support several modes of

instruction including articulate experts with capabilities for demonstrating and explaining task performance, critics for giving students very specific diagnostic feedback following practice, and intelligent microworlds for guiding student exploration and inquiry.

Ritter, F. (1986) "OREO - Adding Orientation to a Dynamic Qualitative Simulation". BBN Technical Report, October. Submitted to Third International Conference on Artificial Intelligence and Education, University of Pittsburgh.

Abstract

In order to simulate electrical circuits accurately using a qualitative model, it is necessary to give parts an orientation with respect to the voltage source in the circuit. Mistakes made by beginning students of electricity, such as not finding a short across a part, can often be attributed to incompletely orienting the circuit. Experienced engineers orient circuits successfully, though they usually do not indicate orientations in an explicit way on their circuit diagrams. This paper presents an algorithm for orienting circuits that is based on the way engineers orient circuits. The algorithm can explain its operation. It can recognize shorts, bridge elements, and other paths useful for a quantitative simulation. The algorithm allows qualitative systems to be dynamically altered and is upwardly compatible with quantitative simulations.

White, B.Y. & Frederiksen, J.R. (1986) "Intelligent Tutoring Systems Based Upon Qualitative Model Evolutions". In the Proceedings of the Fifth National Conference on Artificial Intelligence, Philadelphia, Pennsylvania.

This paper is incorporated within the book chapter referenced above. It provides an overview of the rationale underlying the design of intelligent tutoring systems based upon model evolutions. It also goes into some depth to describe the qualitative causal models that we created for instructional purposes.

White, B.Y. & Frederiksen, J.R. (1986) "Progressions of Qualitative Models as a Foundation for Intelligent Learning Environments". Report No. 6277, BBN Laboratories, Cambridge, Massachusetts.

Abstract

The design of our intelligent learning environment is based upon a theory of expertise and its acquisition. We find that when reasoning about physical systems, experts utilize a set of mental models.

For instance, they may use qualitative as well as quantitative models, and behavioral as well as functional models. The transition from novice to expert status can be regarded as a process of model evolution: students formulate a series of upwardly compatible models, each of which is adequate for solving some subset of problems within the domain. Further, students need to evolve not just a single model, but rather a set of models that embody alternative conceptualizations of the domain. Finally, we claim that in the initial stages of learning, students should focus on the acquisition of qualitative models: quantitative models should be introduced only after the domain is understood in qualitative terms.

In this article, we focus primarily on qualitative, behavioral models of electrical circuit operation designed to make the casuality of circuit behavior derive clearly from basic physical principles. The constraints on model evolution, in terms of causal consistency and learnability, are discussed and a sequence of models that embody a possible transformation from novice to expert status is outlined.

The learning environment we have constructed 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 a progression of models that increase in sophistication in concordance with the evolution of the students' understanding of 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.

Feurzeig, W. (1985). "AI Aids for Design and Automation of CAI Programs". In the Proceedings of the Workshop on Knowledge Acquisition for Computer Assisted Instruction, Carnegie Mellon University, U.S. Army Research Institute, Arlington, VA.

Abstract

The problem of preparing high quality computer assisted instruction in areas requiring knowledge intensive skills is discussed. An AI-based approach to aid instructional designers in automating the generation of such instruction is presented. Specific tools and facilities for implementation of several modes of instruction, and for testing and editing of the prototype instructional materials, are described. These methods are designed to be specifically applicable to instruction in the operation and maintenance of complex engineered devices, in tasks such as electronic troubleshooting and hydraulic power plant operation.

Feurzeig, W. (1985) "Cognitive Science, Artificial Intelligence and Complex Training". In the Proceedings of the NATO Symposium on Computer-Based Instruction in Military Environments, Brussels, Belgium, ed. R. Seidel & P. Weddle, Plenum Press, approx. March,1987.

Abstract

An effective program of instruction directed toward the acquisition of complex cognitive skills needs to balance prescriptive tutorial modes with instructional activities that support exploration and practice. This presentation argued that current research on intelligent instructional systems has a strong prescriptive bias, a one-sided focus emphasizing the development of directive tutorial methods and often ignoring those complementary components of a complete learning system which allow the student greater initiative and control. Current work on modelling student knowledge in intelligent tutoring systems was reviewed. The difficulties in diagnosing students' misconceptions, conceptual gaps, and procedural bugs were described. The fundamental instructioanl problem of how the knowledge of a student's misconceptions and bugs can be effectively used to aid the student overcome them and learn the skill being taught, was discussed.

Frederiksen, J.R. & White, B.Y. (1985) "A System for Teaching a Qualitative Understanding of Electrical Circuit Behavior and Troubleshooting". In the Proceedings of the Second International Conference on Artificial Intelligence and Education, Exeter, United Kingdom.

Abstract

The goal of this project was to develop an intelligent tutoring system for teaching qualitative reasoning about electrical circuits in general, and troubleshooting of automotive electrical systems in particular. The system is designed to provide a simulation environment in which students can solve circuit problems. It also serves a tutorial function and can be called upon to solve problems and demonstrate to students the reasoning involved. The instructional objective is for students to acquire, through their exposure to a sequence of carefully selected circuit problems, a sequence of increasingly sophisticated models of circuit behavior.

To this end, we have formulated a series of cognitive models that correspond to different levels of understanding of electrical circuit concepts. Each model is upwardly compatible with higher level models, but is restricted in the set of circuit problems for which it is adequate. While these mental models vary in the complexity of the circuits about which they can reason, they all represent "runnable" qualitative simulations and enable the student (or the system) to predict the behavior of circuits of a given level of complexity.

Circuit problems given to students include (1) making predictions about circuit behavior, and (2) troubleshooting or isolating faults within circuits. Corresponding to each of these two types of problems are two tutoring systems: (1) a qualitative, causal simulation of electrical circuits that illustrates principles for reasoning about circuits; and (2) an "expert" troubleshooter that demonstrates a strategy for isolating faults within circuits and that incorporates the same type of reasoning as that involved in predicting circuit behavior.

These tutoring systems are based upon a qualitative approach to troubleshooting taken by an expert mechanic whom we have studied. His methods are based upon the fundamental idea of a circuit: For a device to operate, there must be an electrical potential across the device. When such an electrical potential exists, a current will flow through the device (provided it is conductive), causing it in some cases to change its state. Knowledge of the device, in the form of a device model, allows one to infer what state the device will enter and under what conditions.

When troubleshooting, the expert's goal is to choose a test point that divides the circuit into two parts and then to infer which portion of the circuit, that in parallel or that in series with a test light, is faulty. When the fault has been isolated to within a portion of the circuit, the expert then moves to a new test point within the faulty part of the circuit and recursively applies the troubleshooting logic. The approach of our expert has the advantage of being generally applicable to a large class of series-parallel circuits. However, it presupposes a knowledge of electrical circuits and requires an ability to reason qualitatively about circuits.

Given the need to teach electrical principles and their implications as a prerequisite to teaching troubleshooting, we created an instructional environment that is capable of demonstrating and providing

practice in applying circuit principles. The basis of this system is a progression of increasingly sophisticated, qualitative causal models that utilize knowledge of the structure of the circuit, the functioning of the devices within the circuit, and basic electrical principles to simulate circuit behavior. These simulations needed to be robust in permitting faults to be introduced or circuits to be modified without requiring a new model for each perturbation in the circuit. By utilizing context free functional models for devices, along with topological search processes for evaluating electrical potential across devices, we were able to construct circuit models that accurately simulate the behavior of a large class of circuits in both faulted and unfaulted states.

For any given circuit in the teaching sequence, the student is asked to predict the effects of faults that the system has introduced, and to locate unknown faults. At any time, the student can call upon a model of circuit behavior to explain the functioning of the circuit, or upon a troubleshooting model to describe how it would isolate a particular fault in the circuit. Each tutorial program utilizes a model that articulates reasoning at a level of explanation that is appropriate for the particular stage in instruction. We are currently conducting research to determine whether the set of activities that we have developed, combined with the explanatory power of the progression of circuit and troubleshooting models, enables students to acquire a qualitative understanding of circuit behavior and of troubleshooting logic.

White, B.Y. & Frederiksen, J.R. (1985) "QUEST: Qualitative Understanding of Electrical System Troubleshooting". ACM SIGART Newsletter, 93, 34-37.

Abstract

In the context of designing a computer-based system for teaching electrical troubleshooting, we have developed a qualitative model of circuit behavior and a model of expert troubleshooting. The purpose of these models is to explain to students the operation of circuits in faulted and unfaulted conditions and to demonstrate troubleshooting techniques. This paper outlines the troubleshooting model and the qualitative causal models of circuit behavior from the perspective of the instructional constraints that contributed to their design.

Feurzeig, W., Frederiksen, J., White, B., and Horwitz, P. (1984) "Designing an Expert System for Training Automotive Electrical Troubleshooting". In the Proceedings of the Joint Services Workshop: Artificial Intelligence in Maintenance, Air Force Human Resources Laboratory, Brooks Air Force Base, Texas, AFHRL-TR-84-25.

Abstract

This paper discusses the preliminary version of QUEST, an expert instructional system for teaching

the basic principles of electrical circuit operation and the skills of circuit troubleshooting. The troubleshooting model which served as the basis for the expert, the Feed-Device-Ground (FDG) strategy, is described together with the other major component of the initial design, the program for displaying circuit behavior. The system used color coding to represent voltage, and simulated motion along wires connecting circuit components to represent current, in a dynamic graphic presentation designed to make these notions transparent to beginning students.

White, B.Y. & Frederiksen, J.R. (1984) "Modeling Expertise in Troubleshooting and Reasoning about Simple Electric Circuits". In the Proceeding of the Annual Meeting of the Cognitive Science Society, Boulder, Colorado.

Abstract

In this paper we discuss the psychological criteria for constructing models of troubleshooting and reasoning about circuits. The focus is on determining how models of circuit behavior influence the learning of troubleshooting and how training in troubleshooting influences learning to reason about circuits.

ORAL PRESENTATIONS

Frederiksen, J.R. & White, B.Y. "Cognitive Models and Skill Acquisition". Paper presented at the Second Workshop on Workload and Training: Individual Differences, Carmel, California, January, 1987.

White, B.Y. & Frederiksen, J.R. "Qualitative Models and Learning Environments for Troubleshooting". Paper presented at the Conference on Intelligent Tutoring Systems: Lessons Learned, Smugglers Notch, Vermont, October, 1986.

White, B.Y. & Frederiksen, J.R. "Qualitative Model Evolutions as a Foundation for Intelligent Learning Environments". Paper presented at the Fifth National Conference on Artificial Intelligence, Philadelphia, Pennsylvania, August, 1986.

Frederiksen, J.R. & White, B.Y. "Intelligent Tutors as Intelligent Testers". Paper presented at the Educational Testing Service, Princeton, New Jersey, July, 1986.

White, B.Y. "QUEST: A Qualitative Physics Tutor". Paper presented at the Eighth Annual Computer Conference, Lesley College, Cambridge, Massachusetts, May, 1986.

White, B.Y. & Frederiksen, J.R. "An Intelligent Tutor Embodying a Qualitative Understanding of Electrical Circuit Behavior and Troubleshooting". Paper presented at the Annual Meeting of the American Educational Research Association, San Francisco, California, April, 1986.

White, B.Y. "What AI Can Do for Physics Education". Invited address at the Winter Meeting of the American Association of Physics Teachers, Atlanta, Georgia, January, 1986.

Frederiksen, J.R. & White, B.Y. "A System for Teaching a Qualitative Understanding of Electrical Circuit Behavior and Troubleshooting". Paper presented at the Second International Conference on Artificial Intelligence and Education, Exeter, United Kingdom, September, 1985.

White, B.Y. & Frederiksen, J.R. "Modeling Expertise in Troubleshooting and Reasoning about Simple Electric Circuits". Paper presented at the Annual Meeting of the Cognitive Science Society, Boulder, Colorado, June, 1984.