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RESEARCH ON EXPERT PROBLEM SOLVING IN PHYSICS

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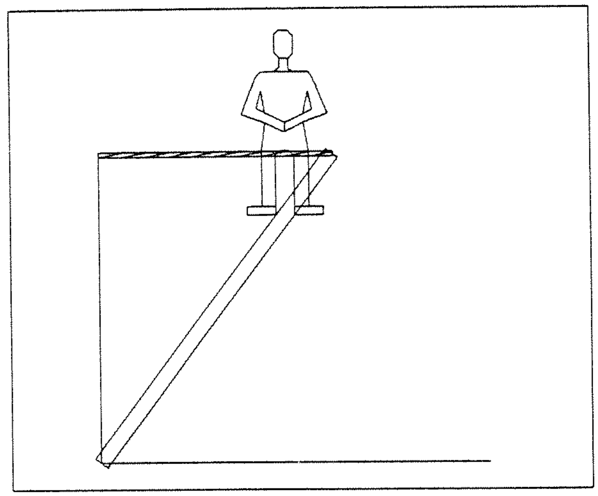
ABSTRACT

Physics problems cannot in general be solved by methods of deductive search in which the laws of physics are stated as axioms. In solving a real physics problem, it is necessary to treat the problem as a "nearly decomposable system" and to design a method of analysis which accounts for the salient factors in the problem while ignoring insignificant factors. The analysis method which is chosen will depend not only on the objects in the problem and their interactions, but also on the context, the accuracy needed, the factors which are known, the factors which are desired, and the magnitudes of certain quantities. Expert problem solvers are able to recognize many frequently occurring problem types and use analysis methods which solve such problems efficiently. Methods by which a program might learn such expertise through practice are discussed.

I INTRODUCTION

We are investigating the cognitive processes and knowledge structures needed for expert-level problem solving in physics. We believe that physics is a particularly fruitful area for the investigation of general issues of problem solving, for several reasons. The laws of physics are well formalized, and there is a large set of textbook physics problems (often with answers and example solutions) available for analysis and for testing a problem solving program. The application of physical laws is considered to be well defined, so that both the method of analysis of a problem and the final answer can be judged as either correct or incorrect. At the same time, physics is considered to be a difficult subject; students find problem solving especially difficult, even when the equations which express the physical laws are available for reference. Although the laws of physics are "well known", nobody has yet produced a program which can approach expert-level problem solving in physics. Such a program would potentially have great value for applications, since the types of reasoning used in computer science and engineering are closely related to those used in solving physics problems. Such a program could also be of value in education, because many of the crucial skills used in solving physics problems are now taught only implicitly, by example; students who are unable to infer the skills from the examples do poorly in physics.



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(THE FOOT OF A LADDER RESTS AGAINST A VERTICAL WALL AND ON A HORIZONTAL FLOOR) (THE TOP OF THE LADDER IS SUPPORTED FROM THE WALL BY A HORIZONTAL ROPE 30 FT LONG) (THE LADDER IS 50 FT LONG . WEIGHS 100 LB WITH ITS CENTER OF GRAVITY 20 FT FROM THE FOOT . AND A 150 LB MAN IS 10 FT FROM THE TOP) (DETERMINE THE TENSION IN THE ROPE)

ANSWER: 120.00000 LB

Figure 1: Example of Output of ISAAC Program

The first author has previously written a program which can solve physics problems stated in English in the limited area of rigid body statics [1,2]; an example of its output is shown in Figure 1. This program, which uses a general formulation of the laws of rigid body statics (similar to the form of the laws presented in modern textbooks), produces between nine and fifteen equations for simple textbook problems for which human problem solvers generate only one or two equations. This somewhat surprising result indicates that the expert human problem solver does not slavishly apply the general forms of physical laws as taught in textbooks, but instead recognizes that a

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particular problem can be solved by applying a special case of the more general law and writes only the equations appropriate for the special case. By doing so, the expert greatly reduces the algebraic complexity of the problem.

II THE NATURE OF PROBLEM SOLVING IN PHYSICS

Most people, even experts, tend to identify the "content" of physics with the equations which express the physical laws. Bundy [3] has written PROLOG programs in which the laws of physics are expressed as Horn clauses and deductive search is used to find answers to problems posed as sets of predicates. As noted by Larkin, McDermott, Simon, and Simon [4], novice problem solvers do tend to use an "equation-driven search", working backwards from the desired quantity until the equations they have invoked can be solved; experts, however, usually work "forward" from the given information until the desired unknown has been found. Experts do not often verbalize the equations that they are using, but usually only verbalize intermediate "answers".

The identification of physics knowledge with the equations which express physical laws and the notion that search is the primary mechanism used in solving physics problems are unsatisfying because they fail to account for several observed phenomena. Why is physics hard? If physics were "only" the equations for the laws, these equations could be collected in a reference book (along with tables of integrals and such), and the physics course could be dispensed with. Why does practice help? What is expertise in physics, i.e., what does the expert have that the novice lacks that enables the expert to perform so much better? Superior algebraic skills alone cannot account for the difference. What is the intellectual content of a physics course? Without continued practice, students forget the equations soon after taking the course; what is it that they retain that makes taking the course worthwhile?

We believe that methods which employ deductive search and express the laws of physics directly as predicate calculus clauses (or the equivalent) cannot account for expert-level problem solving ability when a variety of physical principles are involved (say, the principles covered in a first-year college physics course). Indeed, the best ways of solving certain problems are self-contradictory if examined too closely. Consider the following problem (from [5], p. 67):

> A rifle with a muzzle velocity of 1500 ft/s shoots a bullet at a target 150 ft away. How high above the target must the rifle be aimed so that the bullet will hit the target?

An "expert" solution to this problem might proceed as follows: "It takes the bullet 0.1 second to reach the target. During this time, the bullet falls a distance d = (1/2)*g*t**2 , or (1/2)*32*(0.1)**2 ft, or 0.16 ft. So we aim up by that amount to cancel the fall." In this solution, the "expert" has made several conflicting assumptions: first, that the bullet travels in a straight line; second, that the bullet falls from that path as it travels; and third, that the bullet is aimed upward to cancel the fall. Each succeeding assumption invalidates previous assumptions upon which it is based. In fact, the final answer is not exactly right; however, it differs from a more careful calculation for the parabolic path actually followed by the bullet by only about one part in a million.

The "expert" has not solved this problem precisely, using all the applicable physical laws, but instead has treated the problem as a "nearly decomposable system" [6]. Using qualitative knowledge that bullets move approximately in a straight line, the expert has decomposed the motion of the bullet into the dominant straight-line motion and the much smaller fall and upward motion. If we look harder, other decomposition assumptions can be found, viz. that air friction is negligible and that the earth is flat (i.e., that gravity is "straight down"). In fact, the laws of physics <u>cannot</u> be used directly in a deductive fashion to <u>solve</u> problems. For example, Newton's law, which we write compactly as "F = ma", relates the acceleration of a body (relative to an inertial reference frame) to the vector sum of <u>all</u> forces on the body; however, there are infinitely many such forces, and the frame of reference (e.g., the earth) isn't really inertial. Fortunately, in real problems most of the forces on the body are small and can be ignored, and the frame of reference is nearly inertial; using an appropriate decomposition of the problem, a good approximation of the answer to the problem can be found. Thus, solution of a real physics problem always involves treating a nearly decomposable system as if it were actually decomposable. Programs which use deduction to solve physics problems in a "microworld" are able to do so only because the decomposition decisions have been made, by the choice of the microworld and/or by the form in which the problem to be solved is encoded; however, this limits the extension of such a program to wider problem domains where other decompositions of "similar" problems are required.

This view of problem solving in physics suggests answers to the questions posed earlier. Physics is hard because it is necessary to learn not only the equations, but also ways of decomposing actual problems so that application of the equations is tractable. The expert can solve problems better than the novice because the expert recognizes that a given (sub) problem is an instance of a class which can be decomposed in a particular way; this knowledge of how to decompose a real-world problem along lines suggested by the "fundamental concepts" of physics is a large part of what is sometimes called "physical intuition" [4]. The knowledge of how to decompose problems may be retained by the student even though the formulas have been forgotten, and allows problems to be solved correctly even though the formulas have to be looked up again. The expert works forwards rather than backwards because the first order of business is not to deduce the answer from the given information (which is likely to be grossly inadequate at the beginning), but to find an appropriate decomposition or way of modeling the interactions of the objects in the problem. Once an appropriate decomposition has been found, solution of the problem is often straightforward.

III RESEARCH ON PROBLEM SOLVING AND LEARNING TO BE EXPERT

We are currently writing a program to solve physics problems involving a variety of physical principles. Our work on this program is concentrating on the representation of problems, recognition of (sub) problem types which can be decomposed in particular ways, and learning of problem solving expertise through experience. Each of these areas is discussed briefly below.

To insure that the problem solver is not told how to solve the problem by the manner in which the problem is stated to it, we assume that the input will be English or a formal language which could reasonably be expected as the output of an English parser such as the parser in [1,2]. For example, a car in a problem will be presented to the problem solver as "a car"; whether the car should be viewed as a location, a point mass, a rigid body, an energy conversion machine, etc. must be decided by the problem solver. We are developing a representation language which will allow multiple views of objects and variable levels of detail. For example, a block sliding on an inclined plane may be viewed as a weight, a participant in a frictional contact relation, and a location. A car might be viewed simply as a point mass, or as an object with its own geometry and complex internal structure, depending on the needs of a particular problem.

The expert problem solver does not have a single, general representation of each physical law, but instead is able to recognize a number of special cases of each physical principle and use a rich set of redundant methods for dealing with them. For example, in addition to the general rigid body problem, the expert recognizes special cases such as a pivoted linear rigid body acted on by forces perpendicular to its axis. Such special cases often allow a desired unknown to be found using a single equation rather than many, or simplify analysis, e.g. by approximating a nonlinear equation with a linear one. Recognition of special cases is based on context, on what information is known, and on what answers are desired, as well as on the type of object or interaction. Our approach to recognition of special cases is to use a discrimination net, in which tests of features of the problem alternate with construction of new views of objects and collection of information into the appropriate form for a "schema" or "frame" representation of the view. Such a discrimination net can also be viewed as a hierarchical production system, or as a generalization of an Augmented Transition Network [7].

If the recognition of the type of a (sub) problem is done by means of a discrimination net, special cases of a particular kind of physical system can be added to the net by adding discriminating tests for the special cases "above" the point in the net at which the more general case is recognized. We are investigating ways in which knowledge for handling such special cases could be learned automatically from experience in solving problems. One method of initiating such learning is data flow analysis of solutions using the more general solution. For example, if a problem involving a pivoted lever were solved using the general rigid body laws, data flow analysis would indicate that with a particular choice of the point about which to sum moments (the pivot), the "sum of forces" equations would not play a part in reaching the solution. A special case method could then be constructed from the general method by adding tests for the special case to the discrimination net and adding a corresponding "action" part which writes only the moment equation. Other opportunities for special case learning include elimination of zero terms (rather than eliminating them later algebraically), elimination of forces which turn out to be small when calculated, linearization of "almost linear" equations, use of small-angle approximations, and selection of simplified views of objects under appropriate conditions.

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