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ABSTRACT

The research described in this paper leads to an instructional design approach which is an alternative to the consideration of such issues as mathematical skills or level of cognitive development. The approach uses an analysis of traditional instructional tasks to specify the underlying cognitive processes and structures necessary for the successful completion of the tasks; that is, a cognitive analysis of instructional tasks, rather than a logical analysis, is used to arrive at appropriate instructional goals. The approach involves taking a standard form of a question and converting it to a qualitative problem. Appropriate levels of existing relevant knowledge and experience are then determined, and a series of questions and specific, single-observation laboratory exercises are used to gradually develop a schema for the problem solution. The interaction implicit in the strategy allows for the retention of appropriate aspects of existing schemata and the modification of conflicting aspects. Two broad aspects of differences between physics experts and novice physics students relevant to physics problem solving are considered in the approach. These aspects come from recent cognitive psychology research into processes and structures used by experts and novices in physics problem solving and from science education research into student world views. (JN)

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A PERSPECTIVE ON THE DIFFERENCES BETWEEN EXPERT AND NOVICE PERFORMANCE IN SOLVING PHYSICS PROBLEMS

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Introduction

There has been in recent years a dramatic growth of investigations of student world views of force and motion. These investigations, often motivated by a concern with student understanding of mechanics, have reflected a world-wide interest in these issues (e.g., Champagne et al., 1980; Driver, 1980; Gunstone & White, 1980; Hewson, 1981; Osborne & Gilbert, 1979). The existence of world views logically antagonistic to the tenets of mechanics is now beyond dispute, as is the resiliance of these views in the face of standard forms of physics instruction. It seems clear that the significant issues in this area are now the specific instructional implications of these findings.

The instructional problem:

Classical mechanics is widely perceived to be difficult to learn. Researchers considering this phenomenon have often investigated particular variables argued to be prerequisite to successful physics learning, such as mathematical skills, general level of cognitive development, and specific cognitive processes (e.g., Arons, 1976; Hudson & McIntire, 1977; Renner et al., 1978). The usual basic strategy adopted in such investigations is to show a correlation between a student characteristic (such as Piagetian level of cognitive development) and success in physics. Often instruction is then modified to take account of student inadequacies with respect to this concept, and the effect of this modification on learning is probed. However this strategy has produced only limited results (e.g., Mallinson, 1977; Peterson, 1979).

The studies of student world views of force and motion mentioned above provide another perspective on the difficulties involved in learning physics. These studies give empirical support to arguments that students come to introductory physics courses with firmly embedded conceptualizations of how and why objects move. The conceptualizations have features which are broadly Aristotelian. Many writers have commented on the historically great effort involved in replacing the Aristotelian view of motion in physics. Dijksterhuis (1961) goes further:

> To this day every student of elementary physics has to struggle with the same errors and misconceptions which then had to be overcome, and on a reduced scale, in the teaching of this branch of knowledge in schools, history repeats itself every year. The reason is obvious: Aristotle merely formulated the most commonplace experiences in the matter of motion as universal scientific propositions, whereas classical mechanics, with its principle of inertia and its proportionality of force and acceleration, makes assertions which not only are never confirmed by everyday experience, but whose direct experimental verification is fundamentally impossible ... (p.30).

The research described in this paper leads to an instructional design approach which is an alternative to consideration of issues such as mathematical skills or level of cognitive development. This approach uses an analysis of traditional instructional tasks for the purpose of specifying the underlying cognitive processes and structures necessary for the successful completion of the tasks. That is, a cognitive analysis of instructional tasks, rather than a logical analysis, is used to arrive at appropriate instructional goals. In particular, we consider two broad aspects of differences between physics experts and novice physics students which are relevant to physics problem solving. These aspects come from recent cognitive psychology research into processes and structures used by experts and novices in physics problem solving, and from science education research into student world views. From these we advance simple models of expert and novice physics problem solving and then use these models to consider appropriate goals for physics instruction.

Expert and novice problem solving

The focus here is on problem solving studies undertaken in the area of physics. We have discussed elsewhere both studies in other subject areas and the implications of the broader context of current views that learning is an active and constructive process, that existing knowledge/schema are of considerable importance to the process of coming to understanding through individual interpretation of material to be learned (Champagne et al., in Press).

Larkin (1979) analyzed thinking-aloud protocols obtained from experts and novices while they solved physics problems. She found that experts perform an initial qualitative analysis of a problem before using appropriate equation(s) for the quantitive solution of the problem. Novices, by contrast, immediately search for an equation and do this by matching the information given in the problem with terms in the equation. This differance in problem solving process is shown in simple form in Figure 1.

Place Figure 1 about here

It is not only for problem solving processes that expert/novice differences are found. A series of expariments by Chi et al. (in press) has resulted in descriptions of explicit differences in the physics problem solving schemata of experts and novices. In the first of these experiments, subjects were asked to sort physics problems from a commonly used text by whatever criteria seemed appropriate. Novices were found to sort on the basis of the problems' surface structure (objects such as springs and inclinad planes; terms such as friction; similarities between diagrams), while experts sorted on the basis of the problems' deep structure (laws of physics such as Newton's Laws) that are not mentioned specifically in the problem. A replication and extension of this experiment, which verified that the problem schemata of novices are object-oriented while the schemata of experts are principle-oriented, included advanced novices. These advanced novices sorted problems on the basis of principles, but used surface features to rationalize their sorts. This suggests a continuum from object-oriented to principle-oriented schemata. The findings are also consistent with the view that novices have a number of different schemata which might be applied to situations involving motion, while experts have a single schema for such situations Such a view would then have that the process of moving from novice to expert involves, in part, the collapse of and integration of multiple schemata into a single schema. This interpretation is also consistent with the phenomenon observed in studies of student world views of novices switching between an Aristotelian schema and a Newtonian schema as they move from one situation involving force and motion to another.

Chi et al. also asked subjects to elaborate on the concepts and problem features that had been used as a basis for categorization of the problems. These data indicate that the novices have the same information about the physical principles as the experts, but novices fail to link objects and concepts with physical principles because the necessary relations between these elements are lacking. In contrast, for the expert the description of a physical situation immediately evokes an applicable physical principle. This suggests that the expert has information relating to conditions under which the principle is applicable and this information is associated with the principle. Further, there is evidence that the expert's knowledge is organized hierarchically along the dimension of abstractness, a characteristic which allows for either bottom-up or top-down processing. The novice's less-integrated structure does not allow for such flexible accessibility.

The purpose of the fourth experiment in the Chi et al. stud, was to determine the features of the problems on which the experts based their selection of the appropriate physical principle for solution of the problem. The results of the experiment reveal a significant difference in the degree of abstractness of expert and novice representations of problem types and features. Experts immediately abstract a basic solution strategy from the surface features of the problem. In contrast, novices do not distinguish between the plan for the solution of the specific problem and the existence of a general solution plan for the problem type. Further, experts mention transformed or abstracted features while the novices describe the specific objects and physical constructs. This suggests that the expert translates the literal objects and conditions of the problem into canonical objects and, on the basis of this representation, selects the prototypical problem type of which the particular problem is a specific example.

In summary, the Chi et al. study concludes that the following differences characterize schemata that expert and novice physicists apply in the solution of physics problems: (1) The problem-type schemata of experts are based on physical principles (e.g., energy conservation), and those of novices are based on physical objects (e.g., springs and inclined planes) and constructs (e.g., friction and gravity). (2) The contents of the schemata of experts and novices do not differ significantly in information content; however, the novices' structures lack important relations, specifically relations between the surface features of the problem and the scientific principles which are the basis for solutions.

(3) Experts translate surface features of the problems into canonical objects, states, and constructs while the novices represent the problem in terms of the literal objects and constructs described in the text of the problem. (4) Links exist in the experts' representations of knowledge structures between the abstract representation of features of the problems and the physical principles which are the basis for the solution of the problem. (5) Experts' schemata are arranged hierarchically along the dimension of abstractness; in contrast, the different levels of the novices' knowledge are not well integrated, thus preventing easy access from one level of abstraction to another.

Views of force and motion held by physics novices

The results of studies such as those cited in the introduction are briefly summarized here.

Students of physics have descriptive and explanatory systems/schemata for how and why objects move which develop before formal instruction. We shall call these novice schemata "intuitive" systems. Although the intuitive systems differ in significant ways from the systems to be learned in physics (experts' schemata), the two systems use similar vocabulary. However the meanings attached to terms by novices are not in one-to-one correspondence with the physics meanings (e.g., acceleration, force). Intuitive systems frequently co-exist with ideas derived from instruction, even among successful physics novices. This co-existence is often possible because novices learn the physics systems at the verbal level only. It is also clear that intuitive systems can influence observations by novices of physical situations.

Models of expert and novice problem solvers

By combining these details of differences between physics experts and novices with the conclusions of the Chi et al. study it is possible to elaborate the initial model of expert/novice problem solving shown in Figure 1. The resulting models, shown in Figure 2, are still simple representations. It should be noted that the two schemata depicted in the novice model are most likely to be several schemata. The evidence is strong that a novice will have both a number of schemata derived from the real world and a number of schemata derived from physics instruction.

Place Figure 2 about here

By comparing these representations of experts and novices, we can deduce some appropriate goals for the teaching of physics problem solving skills to novices. In broad terms, these are the development of appropriate schema change and integration, and the acquisition of strategies of qualitative analysis. It is clear that the first of these (schema change) is not an easy goal to achieve. Our own early attempts, based on a more general consideration of the problem, have met with only limited success (Gunstone et al., 1981). It is also clear from inspection of introductory physics courses and texts that the second goal (qualitative analysis) has previously received little, if any, attention.

In the concluding section of the paper we briefly consider some instructional implications of these goals.

Instructional implications

An obvious question resulting from the above is "what experiences do experts have which might result in the described differences?" There appear to be three forms of such experience:

(1) additional formal instruction; (2) more practice in solving problems;

(3) more extensive verbal interactions about physics or more experience in organizing physics information for the purpose of communicating it to others. For two reasons the third of these is the most interesting from the perspective of instructing novices. Firstly, it is the only one which is readily translated into an instructional context for an introductory physics course. Secondly, as discussed above, it is the links in experts' knowledge structures rather than the knowledge itself which appears to distinguish experts and novices - and the prospect of enhancing the development of such links in novices through verbal interaction and communicating to others about physics is, at the very least, logically reasonable. Further, current views of the process of schema change support the proposition that a dialectical process appears to be necessary (e.g., Anderson, 1977; Collins & Stevens, in press).

As a consequence of these arguments, we hypothesize that an instructional dialogue based on the qualitative analysis of problems holds promise for the attainment of the two broad goals listed above. Some specific examples of such an instructional form have been given elsewhere (Champagne et al., in press). In summary, the approach involves taking a standard form of question, such as a rifle and bullet question where a numerical value for recoil velocity of the rifle is asked for, and converting it to a qualitative problem, such as asking how the speed with which the bullet leaves the rifle compares with the speed of the rifle at that time. (This also brings the question somewhat closer to a general problem form than is the more normal numerical example.) Appropriate levels of existing relevant knowledge and experience are then determined, and a series of questions and specific, single-observation laboratory exercises are used to gradually develop a schema for the problem solution. The interaction implicit in the strategy allows for the retention of appropriate aspects of existing schemata and the modification of conflicting aspects. The next stage of our work will involve an investigation of the extent to which our instructional forms can achieve these goals.

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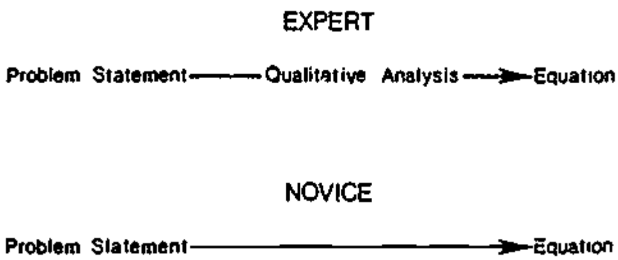

Figure 1: Expert and novice problem solving strategies.

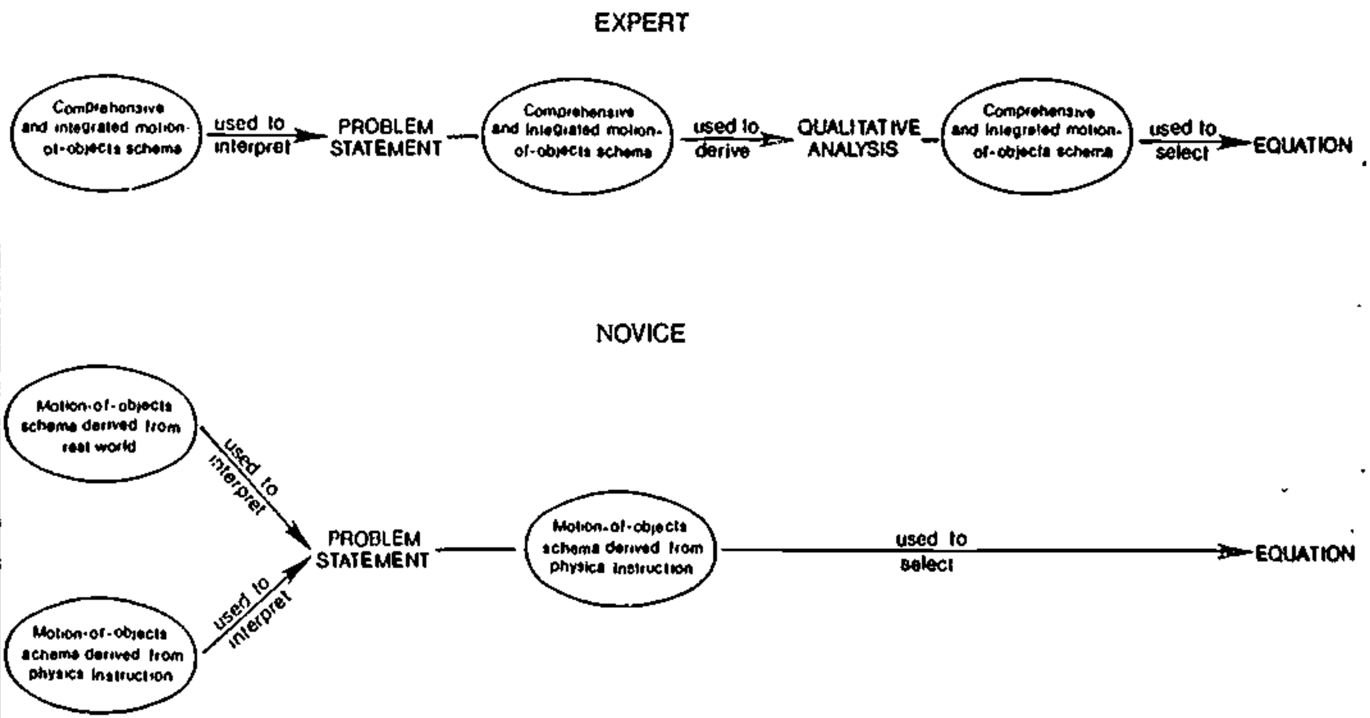

Figure 2: Problem solving strategies and schemata of expert and novice.