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ABSTRACT

During the summer of 1986 a conference funded by the National Science Foundation (NSF) was organized to assess the current state of cognitive research on the psychology of physics problem solving, and to examine the needs of physics instructors and instructional designers that must be addressed by a psychological theory of physics problem solving. This paper outlines a consensus model of the novice physics problem solver that was identified at the conference. It describes a general perspective and a frame of reference about physics problem solving, and indicates some of the disagreements. The paper focuses primarily on the observation that novices often have multiple interpretations of physics concepts. Both theoretical and practical implications of this observation are discussed. It is suggested that this framework be used to interpret many efforts to design effective physics instruction, particularly those concerned with problem solving performance and learning. (TW)

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Introduction

For some time now, there has been great interest in studying what students know about science concepts, how they learn and use those concepts, and how science teachers can improve instruction so that students can develop an adequate conceptual understanding. This broad area of study has attracted interest from several disciplines, including developmental psychology, information processing psychology, science education, and the hard sciences such as physics. We have all found this area of research interesting because it is challenging, embodies theoretically interesting issues, and has great practical pay-offs. Each of us approaches the problem from our own theoretical perspective, focusing on different aspects of the problem, often investigating the issues in different domains of science, such as in physics, chemistry, or biology. That so many different kinds of research have been done is a testament to the complexity of the problem.

However the diversity of our attack does engender some difficulties. We sometimes have difficulty understanding and synthesizing research findings from other disciplines because they are cast in terms foreign to our own. Further, similar issues (e.g., naive concepts) have been investigated, but often in different topical areas (e.g., photosynthesis and mechanics), so it is sometimes difficult to see what generalizations should be made from these studies.

Last summer, an NSF-funded conference of educators, psychologists, and physicists convened to assess the current state of cognitive research on the psychology of physics problem solving, and to examine the needs of physics instructors and instructional designers that must addressed by a psychological theory of physics problem solving.

Today's symposium reports some main themes from the conference, providing an overview of current theory and research on novice physics learning and problem solving. In this paper, we outline a consensus model of the novice physics problem solver identified at the conference. We describe a general perspective or frame of reference about physics problem solving research conducted from a cognitive perspective, even if there may be disagreement about the precise formulation of each point. Points of serious disagreement arise when we try to further refine the general analysis given here, and some of these points will be taken up in the paper by diSessa and Wiser (1987).

This framework can be used to interpret many practical efforts to design effective physics instruction. The perspective we present here serves as background to the three papers in this symposium that report instructional efforts (Clement, 1987; Minstrell & Champagne, 1987; White & Frederiksen, 1987). While we will only sketch the arguments, the other presenters are responsible for developing and supporting them in some detail.

Overview of Physics Problem Solving

One arena in which students are expected to exhibit their conceptual understanding is in solving physics problems. There has been substantial progress in applying cognitive approaches to understand problem solving in physics. The basic model that we work from is used generally to analyze complex problem solving. In highly simplified terms, the main stages of problem solving are: reading the problem; interpreting the problem into an initial representation, which includes using prior beliefs; and operating on and transforming that representation with a variety of strategic and knowledge-based methods to arrive at a solution. Starting with this general perspective, cognitive research has developed methodologies for eliciting performance data that can be used to describe cognitive structures, and we are now starting to detect and describe detailed patterns and characteristics of novice problem solving in physics and other subject-matter domains.

A common observation in many studies across a variety of domains is that many details of problem solving depend on the content and nature of the initial problem representation. Another common pattern is that, in semantically rich domains such as physics, conceptual understanding is used to interpret the problem and to guide the construction of a problem representation. Hence, if we are to understand how subjects solve problems, we need to focus on the beliefs they use to arrive at their initial representation. Many of the participants at the NSF conference have focused their research efforts on just this issue of conceptual understanding.

In this paper, we shall focus on characteristics of novice knowledge and its application in problem solving. These descriptions are first steps to a primary goal in much of the cognitive research on physics problem solving: to characterize deep understanding of the canonical subject matter of introductory physics courses.

Knowledge Representation

Multiplicity is the main message in our description of novice knowledge representations for solving a range of related physics problems. Although most of these multiplicities should be familiar to anyone who has worked closely with the subject matter, their psychological implications are starting to emerge as we consider them in relation to problem solving performance and learning. Our discussion will highlight several aspects of multiplicities. We do not attempt to enumerate all their details and properties.

Knowledge about physical-science subject concepts are often contained in multiple structures. Here are some examples involving friction. Imagine that we ask a student: "When a block is sliding down an incline, is there any friction?" Students often say, "Yes, there is friction because the block is moving and in contact with the incline." We then ask: "If the block is stopped on the incline, is there any friction?" A typical response is, "No, because the block isn't moving." Finally, we ask, "Would it be easy to push the block up the incline?" and students often respond, "Well, if I tried to push that block uphill I would have to overcome gravity and friction, so I guess it would be hard."

This idealized, but typical, protocol shows that the student uses two forms of a concept of friction. One form is embodied as a propositional rule: if two objects are in contact and moving relative to each other, there is friction. The other form is kinesthetic and based on imagining the action of pushing an object. These alternative forms of the concept illustrate some important properties of the psychological representation of conceptual knowledge:

1. Novices often have more than one interpretation of a given physical-science concept, such as density, friction, and force.

2. The format of these alternative representations may differ, including verbal descriptions, equations, or sensory-motor representations.

3. Conceptual knowledge may be in the form of declarative facts, procedural rules, or schematic relations.

4. The information contained in each conceptual representation may differ. That is, if different interpretations of the same concept are applied to the same problem, then different answers are sometimes produced. In the friction example just discussed, if a procedural rule is used, the student asserts there is no friction when the block is at rest; if a kinesthetic interpretation is used, the student concludes the exact opposite, namely, that there is friction. In the former case students typically argue: "If the block is at rest, there is no friction, so it should be easy to move it; but if it is moving, there would be friction, and it should be hard to keep it moving." In the kinesthetic interpretation, a typical student comment is: "Well, once I get it going, it's pretty easy to keep it moving so there must be less friction."

5. The conditions under which each concept is invoked may differ. In the friction example, asking the student about an object at rest invokes the rule form, whereas if he is given the condition of pushing the block, he uses the other form. The conditions associated with each rule need not be disjoint and may be partially overlapping.

The preceding list considers characteristics of the representation of a physical science concept. We have not considered the characteristics of the canonical subject matter to which these concepts are applied. In fact, we also find multiplicities in the relation between a single problem and the physical principles that can be used to solve that problem. For example, in determining whether a block will float in a liquid, one could analyze the problem using a force analysis, a pressure analysis, an energy analysis, Archimedes principle, or a comparison of densities. If the information contained across naive views about these principles is not consistent, then use of different principles would result in different answers, even to the same problem.

Implications for Research on Novice Physics Problem Solving

The existence of multiple representations with different psychological forms and content shows that a student's beliefs about a physical-science concept are not best characterized as a singular or uniform point of view. If students had but one idea about a concept, our experimental designs could be rather simple. We would only need to present a stimulus that elicited the concept and listen to what the student had to say about it. However, the term "concept" may apply to a richer and more varied set of cognitive structures than previously thought. Consequently, researchers, instructional designers, and teachers must be sensitive to this complexity. In the remainder of this paper, we shall first consider implications for planning further research about physics problem solving and interpreting student performance. Then we shall consider implications for developing instruction that fosters conceptual understanding.

Research Implications

Designing empirical studies. Figure 1 shows a more complex design required to reveal the rich details of a student's beliefs. The right column refers to a set of problem situations, each associated with features that are important to a student. The left column refers to different forms of a concept that can be applied to the situations. You will note that each form of the concept is associated with conditions of applicability that govern its use and that are related to the stimulus features in a problem situation. Considering the first stimulus, we see that the first form of the concept is applicable. If we ask students about that stimulus, his comments reflect on that form of the concept. Considering the second stimulus, we see that two different forms of the concept can apply. Only by presenting students with both stimuli will we find out about both forms of the concept. Only by being clever in our design will we find the second stimulus can elicit both forms of the concept.

Given that the psychological representations associated with a concept may be invoked in different situations, a range of situations should be presented to students so that each range may

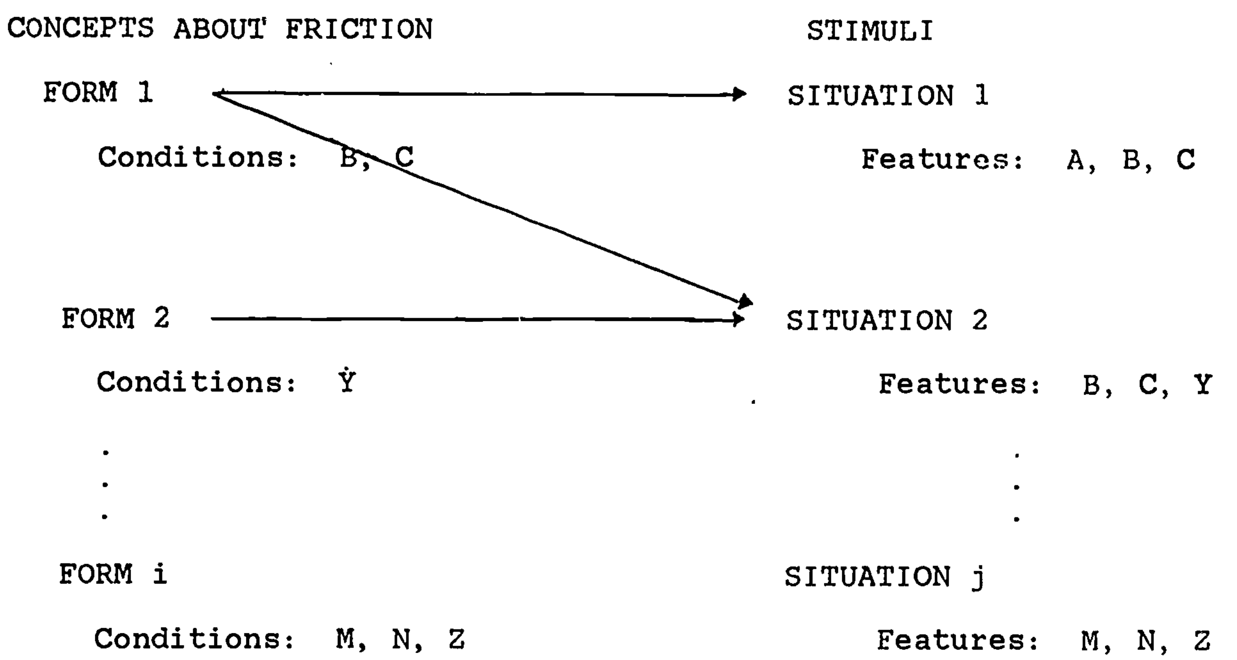

Figure 1: Complex design needed for assessing conceptual knowledge

invoke its associated form. Investigation of reasoning across a range of situations sheds light on the content of one form of the concept; comparison of stimulus values across instances that invoke different forms associated with a concept can be used to define the boundary conditions of each form. The complexity in experimental design and the close attention to selecting stimuli are required if one aims to have a reasonable assessment of a subject's conceptual knowledge. This allows us to gain a more complete view of the student's beliefs, and we begin to pay attention to other aspects of knowledge, such as the conditions of applicability associated with a belief.

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Interpreting student performance. This analysis of student knowledge has important implications for interpreting student performance in reasoning about physics problems. Errors in performance are taken as an important indicator of understanding. Generally, when students answer correctly, they are credited with possessing some knowledge or skill; incorrect answers indicate a flaw in the student's knowledge. At one time, it was believed that errors were due to missing knowledge, and, of course, there are many cases when that is true. The identification of misconceptions adds another source of errors in problem solving performance.

The existence of multiple representations requires even more forces are exerted against the pull of gravity. This view is in error when applied to the case of a block on an inclined plane; the normal force is perpendicular to the plane rather than opposite to gravity. However, in the case of a block resting on a horizontal surface, the misconception provides a correct answer: the normal force is perpendicular to the surface. Thus, if we had asked the student only about normal forces on horizontal surfaces, we would conclude he had the right idea about normal forces and we would be in error.

Third, misunderstandings and contradictions often exhibited by novice physics problem solvers may not reflect flaws in their logical ability. An alternative explanation can be derived from the existence of multiple conceptions. For example, when asked "When a person sits on a bed, does the bed exert a force on the person?" and "When a block sits on a table, does the table exert a force on the block?" naive subjects often give answers an expert would consider inconsistent: "The bed produces a force but the block does not." Based on such a pattern of responses, we might conclude the subject is inconsistent and unable to reason logically. However, the existence of multiple conceptions offers a different interpretation that can be supported by data: the subject may simply have one view about beds and another about tables. That is, he or she may be able to imagine a mechanism by which a bed could produce such a force but unable to construct such a mechanism for tables. In this situation, it is not the reasoning that is inconsistent; rather it is the set of beliefs that are used in reasoning about this class of problems. In such cases, novice subjects may be better characterized as locally consistent in their reasoning but as possessing globally inconsistent beliefs.

Fourth, if a student makes an error on a problem, we cannot conclude that the student does not have any appropriate interpretations of the target concept. The student may have a correct form of the concept but have inappropriate conditions of applicability. As the bed and table examples show, novice subjects may have a belief about normal forces that is valid but they do not apply it in all appropriate cases.

Finally, this view helps to account for aspects of performance that seem perverse. For example, students often say one thing if we present them with one problem but respond quite differently in another case. Is this because they are inconsistent? confused? forgetful of what we taught them? The notion of multiple beliefs offers another interpretation: students say different things because they are using different interpretations of a concept.

Of course, most physics problems require application of more than one concept. For example, if asked to compute the magnitude of the force due to friction for a block on an incline, students need to use concepts about forces, principles of motion, and vector mathematics. Since students may have several different forms for each of these concepts, the psychological analysis of the concepts underlying problem solving can become quite complex. A slight variation in stimulus features may cause the student to select an alternative form of only one concept or may result in wholesale changes in each form of each concept. Hence, minor variations in the problem can be associated with performances that vary only a little or a great deal. The analytic difficulty is further compounded by the fact that stimulus variations to which a student is sensitive may be quite different from those important to a teacher or physicist.

An unresolved theoretical question. The perspective of multiple conceptual forms raises an interesting theoretical question discussed by diSessa and Wiser. Suppose we present students with a stimulus that requires using several of their conceptual forms. How do they decide which to apply? One view is that knowledge is so fragmented that selecting knowledge is very much like ordering from a Chinese menu. That is, the student picks one form of a concept from column A and another form of a different concept from column B, stirs them together and hopes for the best. According to this view, there is no contingency between the forms selected.

Another possibility is that if students select one form of a concept, they tend to select a particular form of other concepts. Another way to state this case is that students can be viewed as having collections of beliefs that hang together, that form a gestalt; some might even say, the student has a theory. diSessa and Wiser will present both sides of this argument: do students have a point of view, or theories if you will, or do they only have many fragmented and independent beliefs?

Instructional Implications

Our analysis of knowledge representation and performance has shown that conceptual and problem-solving knowledge used in solving problems is multiple. We have discussed several interpretative difficulties that arise. To recapitulate these points in terms of instructional maxims:

Teachers must be careful to note that a correct answer to a question involving a physical science concept is not sufficient evidence that a student understands the target concept. Students can apply a concept correctly on one problem but make an error on another. Students may be using different interpretations of the same concept. Furthermore, students may apply a different concept in other cases. Hence, instruction and assessment must occur over a range of problems, so that students are given multiple opportunities to demonstrate their knowledge. Only then might students exhibit the several forms of the concept.

There is no doubt that verbal instruction plus application of formulae to solve quantitative problems is not usually sufficient for developing an understanding of physics in our students. Internationally replicated results have shown that students could obtain high marks in their school and university courses, but not answer reasonably straightforward questions about the physical implications of these formulae. For example, students could accurately calculate the time for free fall of objects with different masses, but could not correctly describe what would happen if two objects of different masses were released from the same height at the same time. These results motivated several attempts to develop student understanding. One promising hypothesis was that clear demonstrations would help students develop appropriate understandings. Another hypothesis, bolstered by Piagetian theory, was that forcing students to confront contradictions in their thinking would lead to appropriate cognitive resolutions. In fact, such efforts to create these conditions have found that students misinterpret the demonstrations, do not recognize the contradictions, or deny that they are in fact contradictions.

These experiences have lead many researchers to suspect that we must be more systematic about the kinds of problems presented to students and the ways that they are used. The view of the novice problem solver presented here helps to understand the recent attempts at instructional intervention that have been developed. Recognizing that there are multiple conceptions, we can choose the points at which we engage them. Several investigators have tried to start with more or less correct student beliefs and provide systematic problems that serve to highlight relevant distinctions.

The last three papers in this symposium present instructional approaches that not only take cognizance of multiple representations, but exploit their occurrence.

Carefully selected problems. Students usually have some beliefs that are correct but incomplete. Hence, some of their beliefs may be quite adequate but only for a limited range of problems. When forced to apply those beliefs outside of their range, the limited nature of those beliefs becomes apparent. As teachers, when we see such errors, we inform students that they are wrong. How does the student interpret this negative feedback? Was the problem with the way he used the idea? Or the idea itself? If we are clever, we can present students with carefully selected and constrained set of problems in which students are likely to use the correct versions of their beliefs at the right time. After students have strengthened appropriate beliefs and weakened incorrect views from experience with these problems, we can present a wider range of problems that introduce additional aspects of the phenomenon being reasoned about so that the correct beliefs can be extended to a wider range of cases. The paper by White and Frederickson reports the kind oı analysis required to select problems for such an approach and describes its success in leading students through conceptual change.

Bridging analogies. A similar approach, reported in Clement's paper, is to start with a correct belief whose conditions of applicability are too narrowly defined. He describes this use of "bridging analogies" that seeks to extend the scope of situations to which a useful belief is applied.

<u>Peer dialogs</u>. One difficulty in dealing with students is that their beliefs are not often articulated in class. As teachers, we are often more interested in telling students the right way to think than in listening to the way they conceptualize the world. Although this allows us to get through the curriculum, we teach in ignorance about what the student believes. If we know more about how students are conceptualizing and solving problems, then we are better able to form a diagnosis and prescribe a course of treatment tailored to the students' beliefs. In the last paper, Minstrell and Champagne describe a teaching method in which students are encouraged to voice their beliefs, make them explicit, engage in argument, discover the limitations of those views, and through discussion, develop new conceptions.

As we start to develop effective ways to help students develop a deep understanding of subject matter, we shall be in a much better position to develop and test a theoretical account of learning processes in physical science subject matter.

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