STUDENTS' CONCEPTIONS AND PROBLEM SOLVING IN MECHANICS

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INTRODUCTION

Results from research on student understanding in physics indicate that certain incorrect ideas about the physical world are common among students of a wide variety of national backgrounds, educational levels and ages. There is considerable evidence that university students often have many of the same conceptual and reasoning difficulties that are common among younger students. There is often little change in conceptual understanding before and after formal instruction. Moreover, students are often unable to apply the concepts that they have studied to the task of solving quantitative problems, which is the usual measure for student achievement in a physics course.

The number of empirical studies on student understanding in mechanics exceeds the number in all other domains combined. We have not attempted to summarize all the research that has been done. An important criterion for the choice of studies has been the degree to which the findings are directly applicable by university faculty to the preparation of teachers. In making this judgment, we have drawn on many years of experience in preparing elementary, middle and high school teachers to teach physics and physical science. Another consideration that has entered into the selection of references has been their relative accessibility to physicists in all countries. Physics publications have been given preference over less readily available references. Because of the rapid growth in the research literature, we have limited this review mostly to studies conducted among students at the university level, including prospective and practicing teachers. The findings, however, apply equally well to high school students and, in some instances, to children in the elementary grades.

INVESTIGATION OF STUDENT UNDERSTANDING

In this section, we give a brief overview of the current state of research on conceptual understanding and problem-solving ability in mechanics. Although instructors had long been aware that this material is difficult for students, the extent of the problem was generally not recognized until physicists and science educators began to conduct systematic investigations and document the results.

CONCEPT DEVELOPMENT

An earlier review of research on conceptual understanding in mechanics identified certain features that should be taken into account in interpreting the results of research (McDermott, 1984). The characteristics of an investigation that can affect the outcome include: the nature of the instrument used to assess understanding; the degree of interaction between student and investigator; the depth of probing; the form of the data; the physical setting; the time frame; and the goals of the investigator.

Kinematics

A study conducted among students taking introductory physics at a large university probed student understanding of the concepts of position, velocity and acceleration in one dimension by examining whether students could apply these concepts correctly in interpreting actual motions of real objects (Trowbridge and McDermott, 1980; Trowbridge and McDermott, 1981). During interviews, students observed two motions and were asked to compare velocities and accelerations. After instruction, about one-fifth of the students confused the concepts of speed and position. Virtually every failure to make a proper comparison could be attributed to the use of a position criterion to determine relative velocity. Confusion between the concepts of velocity and acceleration was even more common. Many of the 200 students who participated lacked even a qualitative understanding of acceleration as the ratio \( v/\Delta t \).

Another study examined 'spontaneous' reasoning in kinematics among 700 first and fourth-year university students and 80 eleven-year old children (Saltiel and Malgrange, 1980). The students were asked to solve paper and pencil exercises involving uniform motion in Galilean reference frames. Analysis of their attempts to describe the motion revealed that many students were inappropriately using a causal model (i.e., invoking forces or other 'causes' of motion).

In a study of student understanding of two-dimensional motion, diagrams of trajectories of moving objects were shown to five students in an introductory university course and to five physics faculty (Reif and Allen, 1992). The participants were told whether the objects were speeding up, slowing down or moving with constant speed and were asked to draw the acceleration vectors at specified points. The novices did very poorly at these tasks; even the experts had some difficulties. A detailed analysis of how the two groups approached these tasks enabled the investigators to identify the underlying knowledge and skills required for successful performance.

Researchers from several countries participated in another study in which high school and university students were interviewed on their understanding of displacement, velocity, and frames of reference (Bowden et al., 1992). The results demonstrated the contextual nature of learning and showed that, as problems become easier to solve in a quantitative manner, it becomes more difficult to differentiate among students on the basis of their level of understanding of basic concepts.

Some investigations have focused on student understanding of the graphical representations of motion. A descriptive study that extended over several years and involved several hundred university students helped identify a number of common difficulties encountered by students in making connections between the kinematical concepts, their graphical representations and the motions of real objects.
Results from research have repeatedly demonstrated that students often emerge from introductory physics courses with many of the same incorrect beliefs that have been found to be prevalent before instruction. Misconceptions about the relationship between force and motion have been extensively studied. Less well documented are difficulties students have in interpreting the relationships between force and more complex concepts, such as work, energy and momentum. Below is a small sample of investigations on student understanding of dynamics.

Dynamics

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Prior to instruction, more than 100 students in an introductory university mechanics course were given a short-answer test on concepts of force and motion (Champagne et al., 1980). The test used a technique abbreviated as D.O.E. (demonstration, observation, explanation). The results revealed that the students, who had previously studied physics, had many incorrect ideas: a force will produce motion; a constant force produces constant velocity and the magnitude of the velocity is proportional to the magnitude of the force; acceleration is due to an increasing force; and in the absence of forces, objects are either at rest or slowing down. The results of another study also indicated that both before and after an introductory course in mechanics many students seem to believe that motion implies a force (Clement, 1982). The study involved written tests and interviews about a pendulum and a coin tossed in the air.

The subject of another investigation was the extent to which individual students consistently applied alternate concepts of force (e.g., 'motion implies a force') in different contexts (e.g., bodies moving and bodies at rest) (Finegold and Gorsky, 1991). Over 500 university and high school students in Israel attempted written tests, while 35 students participated in interviews. The test consisted of questions about the forces acting on various objects such as a book at rest on a table, a pendulum bob, a cannonball in flight, etc. For questions concerning objects in motion, the authors found that students who included a force acting in the direction of motion only included this force in some situations. The belief that no forces act on an object at rest was prevalent.

A study was conducted among European students drawn from the last year of secondary school through the third year of university (Viennot, 1979). Responses to paper-and-pencil exercises on situations such as a mass oscillating on a spring were analyzed. The results indicated that many students assume a linear relationship between force and velocity.

In a study involving curvilinear motion and trajectories of moving objects, about fifty undergraduates were asked to trace the path that a pendulum bob would follow if the string were cut at each of four different positions along its path (Caramazza et al., 1981). Only one-fourth of the students gave an essentially correct response. About 65% drew a line straight down for the case when the string was cut at the equilibrium position.

Some studies have examined student difficulties with situations involving gravity. A study of several hundred first-year university students in Australia involved the use of simple lecture demonstrations related to gravity (Gunstone and White, 1981). For example, students were asked to compare the time it would take equal-sized steel and plastic balls to fall from the same height. On this task, three-quarters of the students predicted different times. Most believed that the heavier object would fall faster. A tendency to "observe the prediction" was noted. Common incorrect answers, illustrated with student quotes, are discussed in detail in the paper that reports on this study.

Another Australian study was based on questions on a multiple-choice, end-of-high-school examination in physics taken by 5500 students (Gunstone, 1987). The test items were based on situations involving gravity that had proven revealing in previous, smaller-scale studies (see above). Certain incorrect ideas were found to be highly prevalent among this population. One test item concerned an Atwood's machine with two weights initially at rest at the same height. The students were asked to predict what would happen if someone were to lower one weight to a new location, hold it there, and then release it. More than half of the students predicted that the weights would then move. When this task was repeated in an open-ended format, a majority of students who answered incorrectly expressed the belief that the weights would return to their 'equilibrium' position.

In a study of student understanding of the Atwood's machine, it was found that many students had serious difficulties with the acceleration, the internal and external forces, and the role of the string (McDermott et al., 1994). The same research group had also investigated student difficulties with applying the work-energy and impulse-momentum theorems to the analysis of actual motions (Lawson and McDermott, 1987). After studying the relevant material, most of the students were unable to relate the algebraic formalism learned in class to the simple motions that they observed.

The Force Concept Inventory (FCI) is a multiple-choice test developed to assess student understanding of Newtonian dynamics (Halloun...
and Hestenes, 1985; Hestenes et al., 1992). This test is intended to determine whether students are able to distinguish between correct Newtonian answers and popular but erroneous "commonsense" beliefs. The same authors have developed another multiple-choice test, the Mechanics Baseline Test (MBT), which covers a greater range of topics in Newtonian mechanics than does the FCI (Hestenes and Wells, 1992). In a survey of 6,000 high school, college and university students, who had taken the FCI before and after instruction in mechanics, it was found that the largest increase in scores occurred among students who had been interactively engaged in activities that yielded immediate feedback through discussion with peers or instructors (Hake, 1996). This report has been submitted for publication.

Although the results obtained with the assessment instruments described above are encouraging, they should be interpreted with care. It is impossible to tell in any multiple-choice test when a correct answer is given for the wrong reasons (Sandin, 1985). Such tests can be used as indicators of the initial state of individual students. However, as McDermott and her colleagues in the Physics Education Group have discussed, good performance on these tests should be viewed as a necessary but not sufficient condition for the attainment of a proper conceptual understanding (O'Brien Pride et al., 1997).

PROBLEM-SOLVING ABILITY

It has been in the domain of mechanics that the ability of students to solve physics problems has been most thoroughly investigated. Problem solving has been used by cognitive psychologists and cognitive scientists as a context for examining thought processes. Research on problem solving that has direct relevance to the teaching of physics has been discussed in a comprehensive review (Maloney, 1994). In the studies discussed below, the process through which individuals at different stages of expertise in physics attempt to solve problems in dynamics is examined and analyzed.

A study attempted to identify differences in the ways that experts and novices solve physics problems (Chi et al., 1981). The subjects included undergraduates who had completed a single course in mechanics, an advanced undergraduate physics major, a physics graduate student, and a physics professor. Among the findings were the tendency for experts to categorize problems according to "deep structure" while novices tended to categorize according to surface features.

In one study, problem solving was analyzed in terms of three main stages: description and analysis of the problem, construction of a solution, and testing of the solution (Reif, 1983; Reif, 1995). An analysis of these stages indicated that the components of problem solving are too complex to be learned through examples and practice. The ability to solve problems depends not only on the learning of procedures but also on the ability to draw on appropriate ancillary knowledge (Reif, 1985).

APPLICATION OF RESEARCH TO INSTRUCTION

A major motivation for conducting research on student difficulties is to use the results to guide the development of curriculum that matches the needs and abilities of students. The results from all of the studies discussed above are consistent with a perspective on teaching and learning that can be broadly categorized as "constructivist." Two important elements of the constructivist view of how scientific knowledge is acquired can be summarized as follows: All individuals must construct their own concepts, and the knowledge that they already have (or think they have) significantly affects what they can learn. The student is not viewed as a passive recipient of knowledge but rather as an active participant in its creation. This view of learning is in sharp contrast to the transmissionist view in which it is assumed that information can be delivered directly to students in a usable form, if only it is stated clearly enough. The implication is that listening to lectures, reading the textbook and practicing problem-solving should enable them to develop a functional understanding of physics, i.e., the ability to do the reasoning needed to apply appropriate concepts and principles in situations not previously memorized.

Below are some examples of instructional strategies and materials that reflect a constructivist approach. Although taken from curriculum that has been developed in the United States, the examples have much wider applicability. The examples illustrate the application of research to instruction and are also relevant to teacher preparation.

CONCEPT DEVELOPMENT

Instructional materials have been specifically designed to help prospective and practicing teachers develop the conceptual understanding and reasoning skills necessary to teach science as a process of inquiry (Rosenquist and McDermott, 1987; McDermott et al., 1996). This conceptual approach to teaching kinematics engages students in structured laboratory-based activities designed to help them develop a qualitative understanding of instantaneous velocity, constant acceleration and the distinction between these two concepts. There is an emphasis on helping students develop the ability to translate back and forth between actual motions and their graphical representations. These materials have been developed through an iterative process of research, curriculum development and instruction (McDermott, 1991). In addition to systematic research, the initial design of the materials drew on the insights of an experienced instructor who had examined student understanding in less formal ways (Arons, 1977; Arons, 1994).

A study was conducted to examine the disparity between the precise use of technical terms by scientists and the indiscriminate use by students. The results suggest a general instructional strategy for minimizing linguistic complications in the teaching of mechanics. (Touger, 1991).

Ongoing research in the classroom guided the development of an instructional strategy to address the difficulty that students frequently have in acknowledging that a stationary surface can exert a normal force on an object with which it is in contact (Minstrell, 1982). In this approach, the normal force exerted by a table on a book is made plausible by having students consider the book in a series of similar
A general instructional strategy for helping students overcome some common conceptual difficulties involves the use of microcomputer-based laboratory activities (Thornton and Sokoloff, 1990). For example, in kinematics, the students create real time position, velocity and acceleration versus time graphs of motions, including their own. The instant feedback helps make explicit the connections between motions and their graphical representations. These and other microcomputer-based activities have been incorporated into an introductory course that is entirely laboratory-based (Laws, 1991). Evaluation of the curriculum by pretests and post-tests indicates that learning and retention are significantly better than in courses taught by traditional methods. In a different type of laboratory-based approach students perform simple experiments that are designed to form a basis for a Socratic dialogue (Hake, 1987; Hake, 1992).

Interactive lectures have been increasingly used in introductory physics courses as a means of engaging students intellectually. In one new curriculum, the instructor conducts interactive lectures during which students analyze physical situations with the help of worksheets (Van Heuvelen, 1991a; Van Heuvelen, 1991b). The students’ first encounter with a topic is qualitative; quantitative analysis follows. Peer instruction is another approach that has been used to secure the active involvement of students in large lecture-based courses (Mazur, 1996). At several points during a lecture, the instructor presents a qualitative question and multiple-choice responses that together are designed to reveal common conceptual difficulties. After recording their response, the students are asked to converse with their neighbors and to revise their answers if they choose.

Carefully sequenced qualitative questions for use in small group tutorials and in interactive tutorial lectures have been developed to supplement the lectures, textbook and laboratories that characterize traditional instruction (Shaffer and McDermott, 1992). Research has been used as a guide throughout the development of this supplementary curriculum, which has been designed to promote the growth of conceptual understanding and reasoning skills. To foster conceptual change, the materials often make use of an instructional strategy in which the tendency to make a particular error is first deliberately exposed and then explicitly addressed. The procedure may be summarized as a sequence of steps: elicit, confront and resolve (McDermott, 1991).

The process through which students can be encouraged to make a conceptual change has also been examined from several theoretical perspectives. One model for learning describes conceptual change in terms of conflict between the learner's existing conceptions and new conceptions (Hewson and Hewson, 1984). It is suggested that the learner may agree to adopt a new conception if it is 'intelligible, plausible, and fruitful.' There are a number of other factors that are important, including the degree to which an individual student is committed to internal consistency.

It has been suggested that processes of conceptual change can be organized into three types: 'differentiation,' 'class extension,' and 'reconceptualization' (Dykstra, 1992). In differentiation, new concepts emerge from more general ideas (e.g., velocity and acceleration from motion). In class extension, concepts considered different are found to be the same (e.g., rest and constant velocity). In reconceptualization, a significant change takes place (e.g., force implies motion becomes force implies acceleration).

In another model, student knowledge is described in terms of pieces or 'facets' that may be related to content, strategies or reasoning (Minstrell, 1992). An example of a facet is the notion that 'heavier objects fall faster,' an idea that is usually incorrect but may be valid in certain contexts. In this model, instruction is seen as an effort to help students modify existing facets and add new facets. Instruction is viewed as a process of helping students incorporate existing and new facets into a correct conceptual framework.

**PROBLEM-SOLVING ABILITY**

Curriculum has been developed specifically to improve students' problem-solving competence. A series of studies investigated the abilities needed for understanding a relation such as a definition or a law (Reif et al., 1976; Reif, 1981). An instructional strategy was developed to teach the general method of acquiring an understanding of such a relation. An explicit problem-solving strategy, involving the application of the relation was taught. The results of a study on the effects of knowledge organization on task performance suggest that a hierarchical presentation of information improves the ability of students to solve certain types of problems (Eylon and Reif, 1984).

A strategy for teaching problem-solving skills using cooperative groups has been developed in which problem-solving sessions have taken the place of standard recitations as a supplement to labs and lectures (Heller et al., 1992; Heller and Hollabaugh, 1992). Context-rich problems are assigned for group work. These problems differ substantially from end-of-the-chapter problems in traditional textbooks. They place the student in a real situation in which physics must be used to devise a solution to a problem. The information provided to the students may include irrelevant facts and may be incomplete. Tests of the approach helped identify a number of factors that are important for its effectiveness, including the structure of the groups and the training provided for teaching assistants.

Another type of instructional strategy for problem solving was designed for use in large lecture classes. Students are taught to begin the solution of a problem by writing a qualitative description. The students identify the relevant concepts and principles and justify the selection they have made. They then describe how to apply the concepts and principles to find a solution (Leonard et al., 1996).

**COMMENTARY**

Some of the experimental studies discussed above have focused entirely on the identification and analysis of student difficulties, while others have included the design and testing of instructional strategies that address these difficulties. The results from all of these studies, taken together, support the following generalizations on learning and teaching (McDermott, 1993).
Facility in solving quantitative problems is not an adequate criterion for functional understanding.

*Questions that require qualitative reasoning and verbal explanations are essential.*

As course grades attest, many students who complete an introductory physics course can solve standard quantitative problems, such as those at the end of the chapter in a typical textbook. Success on such problems, however, does not ensure that students have developed a functional understanding, i.e., the ability to do the reasoning needed to apply appropriate concepts and principles in situations not previously memorized. For many students, solving such problems is a relatively passive experience. Problems that require qualitative reasoning and verbal explanations demand a higher level of intellectual involvement. There is evidence from research that students who have had experience in solving qualitative problems do as well, and often better, on quantitative problems than those who have spent more time in traditional problem-solving (Shaffer and McDermott, 1992; Thacker et al., 1994). More importantly, students who have worked through qualitative problems do much better on such problems than other students and are able to give much better physical explanations.

This result suggests the following sequence of instruction. The study of a new topic should begin by helping students develop a qualitative understanding of the material from direct experience or observation when possible. Mathematics is often introduced very early in the typical presentation. Unfortunately, once equations appear, students tend to avoid analyzing situations qualitatively. Mathematical formalism should be postponed until after students have had some practice in qualitative reasoning about the phenomena under study. Moreover, students should be asked to synthesize the concepts and mathematics and articulate the relationship in their own words.

A coherent conceptual framework is not typically an outcome of traditional instruction.

*Students need to participate in the process of constructing qualitative models that can help them understand the relationships and differences among concepts.*

Concept development is an iterative process, one of successive refinement. The first encounter with a new concept should be closely tied whenever possible to the observations and experience of students. Successive refinement should take place in a spiraling fashion as students recognize the need to account for new phenomena.

Certain conceptual difficulties are not overcome by traditional instruction.

*Persistent conceptual difficulties must be explicitly addressed by multiple challenges in different contexts.*

In instances in which it is known from research or teaching experience that students will have certain difficulties, it is important that the tendency to make a particular error be deliberately exposed and then explicitly addressed. Once an error is elicited through an appropriate task, the student can be helped to recognize and confront the difficulty. At that point, it is crucial that the instructor insist that the difficulty be resolved. If this is not done, the difficulty is likely to remain latent and arise later in a different context.

Research and experience in preparing teachers have demonstrated the need for special courses for teacher preparation (McDermott, 1990). Two generalizations are especially relevant to the preparation of teachers. Both are strongly supported by research and teaching experience.

Teaching by telling is an ineffective mode of instruction for most students.

*Students must be intellectually active to develop a functional understanding*

and

Most teachers tend to teach as they have been taught.

*Teachers should be given the opportunity to learn the content that they will be expected to teach in the manner that they will be expected to teach.*

REFERENCES


http://www.physics.ohio-state.edu/~jossem/ICPE/C1.html


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Section C1, Student's conceptions and problem solving in mechanics from: Connecting Research in Physics Education

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