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ABSTRACT

This study investigated the effects of constraining freshmen physics students to follow an expert-like approach in analyzing mechanics problems. A computer-based, problem analysis environment was constructed that allowed novices to actively engage in performing a qualitative analysis of problems according to a hierarchy which combined declarative and procedural knowledge. Use of this environment for five hours promoted consistent, measurable shifts from novice-like toward expert-like behavior in several areas. In contrast, no consistent shift toward expert-like behavior was observed in two control groups who spent the same five hours solving problems using more traditional, novice-like approaches. The implications of this research are discussed in terms of instructional strategies aimed at promoting expert-like behavior. (Author)

Promoting Expert-Like Behavior Among Beginning Physics Students*

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Abstract

This study investigates the effects of constraining freshman physics students to follow an expert-like approach in analyzing mechanics problems. A computer-based, problem analysis environment was constructed that allowed novices to actively engage in performing a qualitative analysis of problems according to a hierarchy which combined declarative and procedural knowledge. Use of this environment for five hours promoted consistent, measurable shifts from novice-like toward expert-like behavior in several areas. In contrast, no consistent shift toward expert-like behavior was observed in two control groups who spent the same five hours solving problems using more traditional, novice-like approaches. The implications of this research are discussed in terms of instructional strategies aimed at promoting expert-like behavior.

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I. Introduction

How does a novice physics student become an expert physicist? This is an important question since every time we walk into the classroom we attempt to convey knowledge and procedures that will help our students achieve expert-like behavior. Until recently, little was known about the answer to this question except that substantial time and practice are needed to gain expertise. However, during the last few years research collaborations between physicists and cognitive scientists have begun to address the processes involved in the transition from novice to expert.

In this paper, we report on a study of the effects of structuring the problem solving activities of novices in the domain of elementary mechanics in a way that reflects our understanding of the way expert physicists approach problems. More specifically, we evaluated the effectiveness of a computer-based, problem analysis environment that constrained novices to analyze mechanics problems according to an expert-like concept hierarchy. Of particular interest to us was whether students who had recently completed a calculus-based mechanics course with a grade of B or better would exhibit more expert-like behavior after using this problem analysis environment. To detect possible shifts toward expertise, three problem solving tasks were administered before and after treatment: 1) a problem categorization task assessing ability to decide whether or not two problems would be solved similarly, 2) a qualitative explanation task assessing ability to provide coherent explanations of physical situations, and 3) a problem solving task assessing ability to solve mechanics problems.

We begin with an overview of the physics expert-novice research literature, followed by a description of the architecture of the computer-based, expert-like environment; we also describe the architecture of a computer-based, novice-like environment which was used by novices serving as a control group for the experiments. We then discuss our research findings and conclude with instructional implications.

II. Background

In cognitive science, it is useful to distinguish between two kinds of knowledge: declarative and procedural. Declarative knowledge refers to the principles, concepts, equations and facts necessary to function in a domain. Procedural knowledge refers to those procedures and techniques that are useful for applying declarative knowledge in problem solving situations. Novices and experts manifest distinct differences in how they store declarative knowledge in long term memory, and in how they use it via procedural knowledge to solve problems.

Experts are believed to store declarative knowledge hierarchically.[1-5] The expert's memory store can be thought of as a pyramid, the top of which contains a few select fundamental principles and concepts. The middle levels of the pyramid contain ancillary concepts, while formulas and factual information fill the lower levels of the pyramid. The lower levels of the hierarchy are usually accessed via reference to the connecting subconcepts and to principles from the higher levels of the hierarchy. Thus, the expert's memory store is a richly interconnected network that allows efficient access to information.

In contrast, novices store declarative knowledge in a somewhat amorphous and sparsely interconnected network, with little priority given to fundamental concepts over ancillary concepts and domain-related facts and equations. As the novice learns more physics, this amorphous storage system becomes inefficient and a restructuring toward a more hierarchical system begins.

Support for these contrasting models of the way experts and novices store declarative knowledge has been found in several domains. In one experiment, Egan and Schwartz[6] found that, in contrast to novices, expert electronic technicians were successful at reproducing complex circuit diagrams from memory following brief exposures. The superior recall of these experts was attributed to their ability to chunk individual circuit elements, like capacitors and resistors, into functional unit clusters, such as amplifiers and rectifiers. The ability to apply this hierarchical chunking procedure proved necessary to the superior recall performance of experts. Indeed, experts and novices were equally poor at recalling circuit diagrams constructed by randomly arranging circuit components so that they served no apparent function. Similar hierarchical chunking by experts has been observed in other domains, such as computer programming[7] and chess.[8]

Hierarchical chunking by expert physicists has also been observed. Larkin[9] found that experts engaged in solving classical mechanics problems generated clusters of relevant equations in spurts, and that these spurts were separated in time. This suggests that each cluster of equations was accessed via some principle or concept. In contrast to experts and consistent with the hypothesis of an amorphous memory store, novices generated equations individually, with time gaps separating each equation generated.

The hierarchical nature of the experts' memory store is also supported by a study of problem categorization.[10] In this experiment, novices and experts were asked to sort a stack of mechanics problems written on index cards into piles according to similarity of solution--that is, problems that could be solved using the same strategies were to be placed in the same pile. Results showed that novices relied primarily on the problems' surface features (i.e. problem jargon and descriptor terms) as the classification criteria.

For example, novices placed inclined plane problems in one pile, pulley problems in another pile, problems involving friction in a third pile, and so on. Experts, on the other hand, relied more on the problems' <u>deep structures</u> (i.e. principles, concepts or heuristics that could be applied to solve the problem) as the classification criteria.

The proposal that experts and novices differ in procedural knowledge has considerable experimental support as well. Experts possess an arsenal of procedures, strategies and heuristics for attacking problems that novices do not come close to matching, as the following two examples illustrate. When asked to state the <u>approach</u> they would use to solve a problem, experts provided a strategy describing which principles they would apply, and how they would apply them to solve the problem. In contrast, novices were unable to state a general approach; instead, they actually attempted to solve the problem, giving the various equations they would use.[10] Other studies[3,11-14] indicate that experts use forward strategies to solve problems--that is, they start by deciding which principles apply, then they apply them to generate appropriate equations, and finally they solve the equations for the desired quantity. Unlike experts, novices seldom start by applying principles; they employ a primitive means-end strategy that consists of writing an equation, assessing what unknown quantities are needed to isolate the desired quantity, and then looking for additional equations that relate the unknown quantities to known quantities. This formula-based approach has undoubtably been observed by all who have taught elementary physics courses, and is exemplified by the solid mosaic of equations that fill the "formula sheets" that many instructors allow students to bring to exams.

Given these marked differences between experts and novices, one might ask whether novices can make more rapid progress toward expertise if they are somehow constrained to follow an expert-like approach to problem solving. Two recent studies, one by Heller and Reif[15] and the other by Eylon and Reif[4] indicate that novices can benefit from such constraints. In Heller and Reif's study, novices were trained to generate qualitative analyses prior to solving problems that required the application of Newton's second law. Subjects were required to describe problems in terms of concepts, principles and heuristics. The results revealed that novices substantially improved in their ability to construct problem solutions. Heller and Reif point out that such skills as analyzing a problem in detail before attempting a solution, determining what relevant information should go into the analysis of a problem, and deciding which procedures can be used to generate a sound qualitative analysis of a problem, are skills that are tacitly possessed by experts but seldom taught in physics courses.

Eylon and Reif studied the influence of the form of a physics argument. One group of novices received the argument in a hierarchical format, while the other group received the same argument in a linear, non-hierarchical format. The group that received the argument in hierarchical form performed recall and problem solving tasks significantly better than the non-hierarchical group. These findings indicate that the organization of a presentation can be as important as the content of the presentation in terms of people's ability to assimilate and use the information presented.

In the current study the focal treatment consisted of having subjects analyze problems qualitatively according to a specific hierarchical structure that was managed and administered by computer. The problem domain, which was considerably more ambitious than those in previous studies,[15-16] included all the major topics that are usually taught in an introductory classical mechanics course. In the next section we describe the hierarchical computer analysis environment used in the focal treatment, as well as a novice-like, equation-based environment that was used as a control treatment.

III. Descriptions of Computer Environments

Both of the computer-based environments we will describe here are capable of handling problems relating to topics covered in the first 14 chapters of the introductory text by Resnick and Halliday.[17] However, the problems are treated in quite different ways by the two programs. The Hierarchical Analysis Tool makes explicit both the questions that an expert would ask when attempting to solve a problem and the order in which it would make sense to ask them. In contrast, the Equation Sorting Tool was designed to allow novices to efficiently search for the equation(s) that could be used to to generate an answer to a problem.

A. Description of Hierarchical Analysis Tool (HAT)

The Hierarchical Analysis Tool (or HAT) is a menu-driven, computer-based environment that combines declarative and procedural knowledge in a hierarchical structure. Its design is consistent with our best understanding of how physicists analyze problems. The word "tool" in the name is meant to imply that the environment facilitates constructing a problem's solution, rather than actually supplying the answer.

Simply put, the HAT presents the user with a series of menus requiring responses to well-defined questions that an expert might pose while analyzing an elementary mechanics problem. In the first menu, the user selects one of four general principles that could be applied to solve the problem under consideration. The content of subsequent menus is determined via computer software based on the prior selections of the user, and becomes increasingly specific as one progresses. When the analysis is complete, the Hierarchical Analysis Tool provides the user with a set of equations that is consistent with the menu selections made during the analysis. If the analysis was carried out correctly, then these equations could be used to generate a solution to the problem; however, the user must still manipulate these equations to construct the answer. In the event that inappropriate selections were made, the final equations would nevertheless be consistent with the user's selections, but inappropriate for solving the problem. Thus, the HAT is a flexible, self-consistent resource designed to constrain its user to apply a hierarchical, "top-down" problem solving approach.

It is important to note that the Hierarchical Analysis Tool does not explicitly tutor or provide feedback to the user--it only provides a mechanism that constrains the user to an expert-like approach to problem analysis. The best means of understanding its structure and function is through an example. Let us consider Problem 1 in Table 1.

Figure 1 contains the series of menus and menu selections that appropriately analyze Problem 1. The first menu asks the user to select among four fundamental principles that could be applied to solve a problem. Since this problem can be solved most easily using work and energy principles, menu selection #4 is the appropriate choice. The second menu is more specific and asks the user to describe the mechanical energy of the system. Explanatory information is provided (enclosed in parentheses) to help the user decipher the choices presented.

Procedural knowledge enters at menu level 3; here the user is asked to classify the changes in mechanical energy by considering one body at a time in some initial and some final state. In Problem 1, the block starts out with only potential energy and ends up with only kinetic energy (assuming one takes the potential energy to be zero along the horizontal portion of the track). At the fourth menu the user is asked to characterize the changes in kinetic energy, which in this case are purely translational. The user must then specify the boundary conditions for kinetic energy at menu level 5. To describe the changes in potential energy, the questions of menu levels 4 and 5 are repeated in menu levels 6 and 7.

At menu level 8, the user is asked whether there is more than one body in the system. Since there is not, the next screen provides a summary of the solution plan generated thus far. This summary includes the principle that was selected at the first menu level stated in a general equation form, as well as the specific equations dictated by the selections made during the analysis. If appropriate selections were made, then the general and specific equations can be combined to generate a correct answer to the problem. For Problem 1, the user would have to manipulate the equations given in menu level 9 of Figure 1 to obtain the correct answer, namely, $v = \sqrt{2gh}$.

As mentioned earlier, if the user makes an inappropriate selection at any menu level during the analysis, the end result would be a set of equations that is consistent with the classification scheme selected, but which may be inappropriate for solving the problem. If the user recognizes that a particular set of menu options or the final set of equations do not fit the problem being analyzed, the user has one of two choices: 1) back up to a previous menu and change a selection, or 2) return to the first menu and restart the analysis. The HAT allows the user to list all the menu selections made previous to the current menu to facilitate this process. If any term appearing in a menu is unfamiliar, the user can "window-out" to a glossary and find the definition of the term.

In the final menu presented in Figure 1, the user must decide whether or not the analysis is complete. If necessary, the user can review the set of equations by selecting menu option 3. However, if the problem requires the application of another principle, the user can continue the analysis of the problem by selecting menu option 2. As an example of how one would analyze a two-principle problem, let us consider Problem 2 in Table 1.

Problem 2 can be solved using a sequential application of work-energy and linear momentum principles. To obtain the speed of block m when it reaches the horizontal part of the track the user could use conservation of energy, just as in Problem 1. Then the user could return to the first menu to continue the solution, selecting "Linear Momentum" in order to determine the final speed of the two-block system after the collision. Figure 2 provides the series of menus and choices for the analysis of the "momentum" portion of Problem 2. The end result is two "equation screens" that may be used to solve the problem: one allowing the computation of the speed of m when it reaches the bottom of the ramp, and the other allowing the computation of the final speed of the two-block system.

The Hierarchical Analysis Tool has the flexibility to accommodate problems that could be solved using two distinct methods. For example, to find the velocity of a freely falling object that has descended a distance h, one could select either "Work and Energy" or "Newton's Second Law or Kinematics" at the first menu level. The selection of "Work and Energy" would lead to an analysis similar to that presented in Figure 1. Choosing "Newton's Second Law or Kinematics" would put the user onto a path leading to the kinematic equations governing motion under the influence of a constant acceleration. Both paths would result in equation screens that would be appropriate for solving the problem.

To summarize, the Hierarchical Analysis Tool is a flexible, menu-driven environment that constrains its user to a top-down, qualitative analysis of a problem before any quantitative information is provided. In its current form, the HAT neither tutors, nor provides feedback at any point during the analysis. Finally, the HAT can accommodate the majority of problems encountered in a typical first-semester, calculus-based mechanics course.

B. The Equation Sorting Tool (EST)

The Equation Sorting Tool (or EST) is a sortable data-base of useful equations that was designed to be consonant with the problem solving approaches used by novice physics students This equation data base can be sorted in three ways: 1) by Problem Types, such as "inclined plane" and "falling bodies," 2) by Variable Names, such as "mass" and "velocity," and 3) by Physics Terms, such as "potential energy" and "Newton's Second Law." Figure 3 provides the sorting terms for each category. Some terms, such as "impulse," appear in more than one category.

The Equation Sorting Tool was designed to reflect the predilection of novices to focus their efforts on finding equations that they can manipulate to yield an answer. Given that novices tend to cue on a problem's surface features in deciding what equation to use, multiple surface features are provided among the terms displayed in Figure 3.

The data-base contains 178 equations. It can be reduced to a small number of related equations by performing sequential sorts. For example, to a... : Problem 1 the user may choose to perform a sort according to the ... ie "height." This produces a list of equations that contain the ..." The user can then browse through the reduced e uation list or perfo ...other sort. If the user chooses to perform another sort, a logical choice might be the Problem Type "sliding bodies." The data-base is then reduced to those equations that both contain the variable "h" and are pertinent to sliding bodies. After a few such sorts, the number of equations is reduced to a small, manageable number, from which the user can select the one or two equations needed to solve the problem.

The Equation Sorting Tool, like the HAT, neither tutors nor provides feedback. The EST also has the same glossary feature as the HAT. Basically the EST can be thought of as a lengthy "formula-sheet" that is cross-referenced and accessible via a large list of terms.

IV. Description, Results and Discussion of Experiments

Three experiments are discussed in sections A-C below. Each consisted of a pre-assessment, followed by the treatment, followed by a post-assessment. Pre- to post-improvements were used as a measure of the effectiveness of the treatment.

The 42 subjects who participated in the study were divided into three treatment groups of fourteen subjects each. All subjects had completed a calculus-based, freshman level classical mechanics course with a grade of B or better. In all three treatments, subjects solved 25 classical mechanics problems covering topics from the first 14 chapters of the textbook by Resnick and Halliday.[17] However, the approach used to solve the problems differed significantly across the three treatments. One group solved the 25 problems using the Hierarchical Analysis Tool. Another group solved the problems using the Equation Sorting Tool. The third group solved the problems using a textbook; these subjects were told to solve the problems as they would normally solve homework problems, and they were free to refer to the textbook at any time. All subjects solved five problems at a time during five, one-hour sessions spread over approximately three weeks. All subjects passed in written solutions to these 25 problems; in addition, the key-strokes made by the subjects using the two computer-based tools were recorded for later analysis. The groups using the Hierarchical Analysis Tool, the Equation Sorting Tool, and the textbook will be referred to as the "HAT group," the "EST group" and the "T group," respectively.

In addition to performing the three experiments, we administered a questionnaire to the HAT and EST treatment groups at the conclusion of the study. This questionnaire explored the students' views and attitudes toward the computer-based tool that they used during treatment. The results of this survey are discussed in section D.

A. Problem Categorization Experiment

Categorization of a problem plays an important role in generating a solution. Research findings indicate that a mental representation of a problem is constructed as the problem is read, the formation of which implies some categorization of the problem. For experts, this categorization process suggests possible solution strategies.[14,18-20] Therefore, the appropriateness of the categorization can directly influence the ability to generate a successful solution to a problem.

Since experts and novices employ different criteria in problem categorization, a categorization task is valuable for detecting shifts towards expertise. As mentioned earlier, novices tend to categorize problems according to surface features, while experts tend to categorize according to deep structures. However, it appears that the tendency to categorize problems according to deep structure increases gradually with the level of expertise: Ph.D. physicists are most likely to categorize problems according to deep structure, followed by graduate students and college seniors, while college freshmen rely mainly on surface features.[10,21] This suggested that only modest shifts toward expertise would result from the brief, 5-hour treatments that the novices received.

Therefore, we designed a categorization task that would be capable of detecting the anticipated modest shifts toward reliance on a problem's deep structure. In our task, subjects were presented with a model problem and two comparison problems, and were asked to judge which of the two comparison problems would be solved most like the model problem. Comparison problems were constructed to match their corresponding model problem in one of four ways: 1) surface features, meaning that the objects and descriptor terms in the comparison problem matched those of the model problem, 2) deep structure, meaning that the same physical principle that could be applied to solve the comparison problem could also be applied to solve the model problem, 3) both surface features and deep structure, and 4) neither surface features nor deep structure. These four types of comparison problem were designated: S = Surface features, D = Deep structure, SD = Surface features and Deep structure, and N = No match.

Comparison problems were paired together such that one and only one comparison problem in each pair matched the model problem in deep structure. This constraint allowed the construction of four comparison problem pairings. These pairings were: 1) S-D, 2) S-SD, 3) N-D, and 4) N-SD. An example of five problems (model problem with S, D, SD, and N comparison problems) is given in Table 2.

Assuming a novice-like categorization strategy based strictly on surface features, the following predictions should hold for performance in the four types of items: 1) S-D: the S comparison problem should always be chosen since it is the only one that matches in surface features, resulting in 0% deep structure choices, 2) S-SD: since both the S and the SD comparison problems match the model problem in surface featu . both are equally good choices, resulting in 50% deep structure choices, 3) N-D: either alternative is equally likely to be chosen since neither comparison problem matches the model problem in surface features, resulting in 50% deep structure choices, and 4) N-SD: the SD comparison problem should always be chosen because it matches the model problem in surface features (as well as accidentally matching it in deep structure) resulting in 100% deep structure choices. In contrast, a categorization strategy based on deep structure would result in 100% deep structure choices for all four types. Thus, a shift toward an expert-like categorization scheme should be evidenced by an increase in the percentage of deep structure choices.

The results indicate that the Hierarchical Analysis Tool did promote a shift toward reliance on deep structure for categorizing problems. Table 3 shows the overall performance of the three treatment groups on the 20 items used in the categorization task, where the entries indicate the percentage of deep structure choices. As can be seen from Table 3, the performance of the HAT group increased by ten percentage points after treatment, whereas the other two groups showed no improvement. The improvement of the HAT-group was statistically significant.

For the HAT group, increases in the number of deep structure choices occurred for all model problems and all item types. The improvements of the HAT group on the four item types can be seen in Table 4. They improved at least six percentage points in each of the four item types, with the most dramatic improvement (17% increase) occurring on the S-D items where surface features and deep structure are in direct competition.

The results of the categorization experiment suggest that a hierarchical approach to problem analysis promotes a shift in novices' decision making criterion for categorizing problems from one based on surface features toward one based on deep structures. We believe that use of the Hierarchical Analysis Tool promotes this shift because it highlights the importance of applying principles to solve problems by asking users to select the applicable principle in the very first menu they encounter. The significance of this shift is underscored by the facts that the treatment lasted only 5 hours and that no feedback was provided to let the students know whether or not they were using the HAT appropriately.

B. Explanation of Physical Situations Experiment

The ability to explain physical situations is clearly an important aspect of expertise. Experts are more capable than novices of both verbalizing problem solving strategies and drawing on principles and concepts in constructing explanations.[10] Such findings suggest that an explanation task could be used to assess shifts toward expertise. In particular, one would expect that any restructuring of declarative knowledge that occurred through use of the HAT would be reflected in a shift toward more concept-based and logically structured explanations. Therefore, we designed a task in which students provided qualitative explanations of physical situations.

The explanation task consisted of two equivalent pre- and post-tasks containing two questions each. Each question presented a physical set-up and asked the subject to explain what would happen when a particular change is made in the set-up. The two pairs of questions used in the pre- and post-task, denoted as Set A and Set B, are shown in Figure 4. The subjects were instructed to write out explicitly the reasoning behind their explanations.

Each subject was free to choose which variables should be addressed and how to structure the explanation (e.g, how qualitative or quantitative it should be, and whether to emphasize concepts or formulas). Half of the subjects in each of the three groups received Set A before the treatment and Set B after the treatment, while the other half received the sets in opposite order.

The explanations were evaluated in terms of the level of use of the work-energy concept, since this concept could be used to appropriately discuss all four questions. A quantitative measure of subjects' use of the work-energy concept, designated Level of Concept Use (or LCU), consisted of the sum of the numerical scores in a number of different categories, which included mention of concept, use of concept in reasoning, justification of conclusions, and correct identification of initial and final states. The average pre- and post-LCU scores are given in Table 5. Note that the HAT group was the only group to show an increase in LCU. In fact, analysis of the data revealed a statistically significant ($p=.05$ level) group-by-time interaction indicating that the difference in performance from the pre- to the post-task differed across the three groups.

These results suggest that use of the HAT promotes the incorporation of more expert-like structure into explanations. That the explanation task is detecting shifts toward expertise is supported by two additional pieces of evidence. The first is a relationship between pre- and post-performances on the explanation task and the problem solving task (to be described in the next section). Subjects who improved most on the LCU measure for the explanation task also made the greatest improvements on the problem solving test.

The second piece of supporting evidence is a relationship between performance on the explanation task and the style of using the Equation

Sorting Tool. The EST could be used in distinctly different ways, since selection could be made from lists of Problem Types, Variable Names or Physics Terms. The Physics Terms category contained entries (see Figure 3) that made it possible for subjects to use the EST in a hierarchical manner by first selecting a governing concept, such as conservation of energy, and then choosing subordinate concepts, such as potential energy and kinetic energy. We found that the subjects who made significant use of the Physics Terms category were those who both showed the largest LCU scores and performed best on the problem solving pre- and post-tests.

In summary, the explanation task suggests that a hierarchical approach to problem analysis promotes a shift in novices' explanations of physical situations in favor of more structured, concept-based explanations. Conversely, those EST subjects who displayed a proclivity toward employing a hierarchical approach when using the Equation Sorting Tool also showed higher Level of Concept Use scores in the explanation task than the EST subjects who employed a more surface-feature, novice-like approach.

C. Problem Solving Experiment

Perhaps the most widely accepted manifestation of expertise is the ability to solve problems. Problem solving is a high-level, cognitively demanding task requiring the harmonious interplay of both declarative and procedural knowledge. To measure the effect of treatment on problem solving, two equivalent tests were constructed in the style of a traditional final exam for a freshman level classical mechanics course. For the pre-assessment, half of the subjects received one form of the test while the other half received the second form; for the post-assessment, subjects received the form that they had not solved on the pre-assessment. Both test forms contained seven problems, with four problems requiring the application of one physical principle for solution, and the remaining three requiring the application of two principles. The topics covered by the seven problems are listed in Table 6.

Subjects were given approximately one hour to solve the seven test items. The tests were graded independently by two physicists in a style similar to that which would be used to grade a final exam. Whenever the score on a test item differed between the graders, the solution was reevaluated and a grade was determined by consensus.

The pre- and post-test scores (given as percent correct) are shown in Table 7 for the three treatment groups. All three groups increased about ten percentage points, with nearly all of the improvement due to performance on the four single-principle problems. The two-principle problems proved too difficult for most subjects.

Although improvements in performance were statistically significant for all three groups, no one group improved significantly more than any other group. This result suggests that, at least for treatments lasting a short period of time, problem solving improvement was primarily due to simple exposure to problem solving activities.

To better understand how the treatments influenced problem solving performance, we compared the performance of the three groups on the 25 problems solved during treatment. Because all subjects were required to provide written solutions to the 25 treatment problems, their responses could be compared. These problems were graded on a basis of two points, with one point given for identifying the correct principle that could be used to solve the problem, and one point given for applying the principle appropriately and arriving at the correct answer. These scores are displayed in Table 8.

Although the HAT group scored lower than the other two groups on both measures, the differences between the groups are not statistically significant. Of more interest is the fact that the HAT group computed the correct answer after identifying the correct principle only 58% of the time, as compared to 74% for the EST group, and 71% for the T group. This finding suggests that subjects had difficulty using the Hierarchical Analysis Tool effectively. If the HAT had been used effectively, the HAT group should have been able to compute the correct solution well over 70% of those times when they identified the correct principle given that the program constructed the exact equations needed to solve the problem. It is possible that simply structuring problem analysis is not sufficient. Intervention strategies, such as feedback and coaching may be necessary to yield significantly greater increases in problem solving performance.

To explore further the nature of novices' difficulties with the HAT we analyzed the key-strokes made during use of the HAT. This analysis confirmed our hypothesis that the subjects had not used the HAT effectively. They were able to reach the correct equation screen for only 49% of the problems. Even when subjects selected the appropriate principle at the first menu level, they had limited success in reaching the correct equation screen (52% success rate).

The HAT group experienced difficulties in four main areas: 1) Selecting the appropriate principle (at menu level 1), 2) Characterizing the selected principle (at menu level 2), 3) Specifying details about ancillary concepts (e.g., what types of forces, or what types of mechanical energy are present), and 4) Specifying the physical situation (e.g., the types and number of objects, boundary conditions, etc.). It was not unexpected that subjects would experience difficulty in selecting and characterizing the appropriate principle, since novices do not routinely analyze problems in terms of major principles and concepts. Of all the paths that terminated with an equation screen, 28% of the paths were incorrect due to the selection of an inappropriate principle at menu level 1, and 31% of the remaining paths were incorrect due to wrong characterizations of the principle at menu level 2.

However, it was surprising that subjects erred so often in specifying details about ancillary concepts and the physical situation, since questions in these areas seem to require less knowledge of higher-level physics concepts. Yet subjects erred (for paths starting with a correct selection at menu level 1) 27% of the time when specifying details about ancillary concepts, and 26% of the time when specifying the physical situation. These two error rates do not differ greatly from those in the first two areas.

In summary, performance of the HAT group on the 25 treatment problems indicates that novices had difficulty solving problems using an expert-like approach. Thus, while performance on the categorization and explanation tasks show that HAT subjects were made more aware of the importance of the major principles and concepts needed for solution, they did not derive maximal benefits from using the HAT. Feedback and/or coaching appear to be needed to insure that novices assimilate the approach provided in the structure of the HAT. Only after assimilation of the approach can we expect to see more dramatic improvements in performance.

D. Students' Views of the HAT and the EST

After completion of the post-treatment tasks, the students were given a written questionnaire which probed their views of the Hierarchical Analysis Tool or the Equation Sorting Tool. The questionnaire contained both multiple-choice and open-ended questions. Table 9 provides the responses of the HAT and EST groups to the multiple-choice questions. Responses to the first five background questions indicate that the majority of students had difficulty remembering what they had covered in their mechanics course. Both groups claimed to become comfortable using their respective computer-based environment by the end of the second treatment session, and once accustomed to the environment, they found it relatively easy to use. Students from both groups found that the problems used in the study were of medium difficulty and typical of the type of problem they encountered in their mechanics course.

Questions 6 through 9 probed students' perceptions of the effectiveness of the computer-based environments. Eleven of the fourteen students in the HAT group would prefer to use the HAT to solve problems if given the choice, whereas only eight of the EST group expressed such a preference. Nearly all students from both groups would like to have had the computer-based environment available while they were taking mechanics. The majority of both groups thought they could solve problems better with the computer-based environment than without. However, opinions between the HAT and EST groups differed on the perception of improved problem solving skills--eleven students thought their problem solving skills had improved as a result of using the Hierarchical Analysis Tool, whereas only six students thought they had experienced a similar improvement from using the Equation Sorting Tool.

Responses to open-ended questions also tended to elicit more positive responses from the HAT users. In response to the question, "What did you like about the computer program?", five students from the HAT group believed that the Hierarchical Analysis Tool helped them think about the problems and highlighted the concepts that could be used to solve them, commenting:

- "It is useful in that it requires a systematic approach to problem solving--develops good habits. This method exposes the fundamental principles involved in each problem. This is very instructive."

- "It made you think about the kinds of basic laws you'd be using Also, it forced you to classify each type of problem."

There were also comments appreciating that the HAT was user-friendly, that it generated formulas that were hard to remember, and that it was more interesting to use than the textbook.

The EST group responded to this question quite predictably--nine of the fourteen students said they liked all those formulas packed away in one neat place, as the following quotes illustrate:

- "All the <u>beautiful</u> formulas"
- "Being able to simply look up equations instead of searching through a book for them."
- "The formulas were helpful along with them being organized into categories."

When asked, "What didn't you like about the computer program?", five students from the HAT group were not convinced that the program would always yield the correct formula:

- "I didn't always feel I could find a workable equation. I wasn't always sure that enough equations were actually in the program."

Three students expressed that they found it difficult to decide how to make the appropriate menu selections:

- "Sometimes I didn't know what to choose among the available choices."

We find it encouraging that at least some students realized they were not making optimal menu selections. Finally, two subjects said they found the conceptual approach too vague:

- "The program is very vague. It only goes over very basic concepts."
- "The first choices [referring to the first menu in Figure 1] were not specific enough for me."

Members of the EST group voiced two major complaints in answering this question. Three students thought that having lots of equations was not enough--in addition, they wanted some advice regarding when to use them:

- "It contained only formulas, not methods of solving problems."

The other major complaint was voiced by four EST users who thought that the variables in the equations should be defined:

- "Sometimes the symbols on the equations were hard to figure out. Maybe have an index?."

Finally, subjects were asked: "Do you have any suggestions for improving the computer program?" Consistent with novice's preference for surface features, several HAT students stated that the program could be improved by having additional, and more specific choices in the initial menus:

- "Perhaps have a more diverse and specific menu"
- "More specified initial choices."

The EST students generally repeated concerns expressed previously: some students wanted more than just formulas provided, including information that could be used to solve the problem:

- "Include methods for solving problems, not just formulas."

Others wanted the variables in the formulas defined.

In summary, the results of the survey indicate that the Hierarchical Analysis Tool was well-received by students. The majority thought they had improved their problem solving skills as a result of the HAT treatment, and would prefer to use the HAT to solve problems if given the choice. Further, the HAT group appeared to recognize and value the focus on principles and heuristics incorporated in the approach. However, some students did not appreciate the value of the concept-based problem solving approach, and requested more specificity in what they referred to as the "vague" initial menu options. The Equation Sorting Tool was also well received, with the majority of users claiming they would prefer to use the EST to solve problems if given the choice. However, in general they recognized the limited benefits that could be derived from merely increasing the efficiency of their hunt-for-an-equation approach; less than half thought that their problem solving skills had improved as a result of using the EST. It was encouraging to find that EST users thought the program could be improved by providing additional information useful for problem solving, rather than simply providing equations.

V. Summary and Instructional Implications

The goal of this study was to determine whether constraining novices to follow an expert-like approach in analyzing problems promotes a measurable shift toward more expert-like behavior. To accomplish this goal we developed a computer-based environment, called the Hierarchical Analysis Tool, that allowed novices to actively analyze problems using an approach that combined the application of declarative and procedural knowledge in a hierarchical fashion. The influence of this tool was investigated using various problem solving tasks covering all major topics from a typical introductory mechanics course.

Our findings indicate that freshman students who had completed an introductory mechanics course with a reasonably good grade can benefit from hierarchically structured problem solving. Use of the Hierarchical Analysis Tool promoted measurable, statistically significant shifts from novice-like toward expert-like performance. There were four salient findings. Users of the HAT: 1) shifted to more expert-like schemes in categorizing problems, 2) provided more structured qualitative explanations of physical situations, 3) significantly improved in problem solving performance (although this improvement was not better than that produced by the two control treatments), and 4) recognized the value of a concept-based problem solving approach, and would prefer to use the HAT to solve problems if given the choice.

We interpret the novice-to-expert shifts exhibited by the HAT treatment group in both the problem categorization task and the explanation task to signify that use of the HAT initiated a restructuring of these subjects' declarative knowledge. These two tasks drew heavily from declarative knowledge that resides at the top levels of the HAT hierarchy where subjects displayed a fairly high level of proficiency (e.g., subjects selected the appropriate principle at the first menu of the HAT hierarchy for over 70% of the treatment problems). On the other hand, in addition to requiring a command of declarative knowledge, the problem solving task also required a command of the procedural knowledge which resided at the middle and lower levels of the HAT hierarchy. We believe that the reason why the HAT group's improvement in the problem solving task was not dramatically better than that of the two control groups was that they had limited success in adapting to the full HAT hierarchy.

Given the brevity of the treatment and the limited success that students had in adapting to the HAT, the improvements exhibited by the HAT group are rather encouraging. Indeed, the key-stroke data shows that during the five one-hour treatment sessions students made appropriate analyses in only one-quarter of all paths through the HAT. Although the HAT poses well-defined, judiciously selected questions at each level of the hierarchical analysis, it appears that without some assistance, the typical good novice is not capable of extracting the necessary salient features from the problem to answer every question appropriately. Therefore, it is impossible to ascertain the full extent of the benefits that novices could derive from using such an approach until they display an ability to adopt and use the HAT appropriately.

We believe that coaching and feedback will be necessary to help students home in on the appropriate usage of the HAT. This view is supported by the findings of Collins, Seely Brown and Newman[22] who searched for, and found numerous common features shared among three learning environments that have proved to be effective at teaching complex cognitive tasks. Although many of the features identified by Collins et al. are incorporated in the HAT, two pedagogical features that are not found in the HAT but which are common among effective learning environments are coaching and reflection. Coaching refers to monitoring students while they carry out a task and offering help aimed at bringing their performance closer to expert performance. Reflection provides the opportunity for students to compare and contrast their own problem solving processes with those of an expert. Since the HAT was designed as a research device and not as a pedagogical instrument, it does not contain these two ingredients.

We believe that with the addition of these two ingredients, the concept-based approach incorporated in the Hierarchical Analysis Tool has the potential for becoming a powerful pedagogical tool for promoting expert-like behavior among novices. Such an approach could begin to address an important shortcoming of current instructional practice, as eloquently described by Collins, et al.:

> "While schools have been relatively successful in organizing and conveying large bodies of conceptual and factual knowledge, standard pedagogical practices render key aspects of expertise invisible to students. In particular, too little attention is paid to the processes that experts engage in to use or acquire knowledge in carrying out complex or realistic tasks. Where processes are addressed, the emphasis is on formulaic methods for solving 'textbook' problems, or on the development of low-level subskills in relative isolation. Few resources are devoted to higher-order problem solving activities that require students to actively integrate and appropriately apply subskills and

conceptual knowledge. ... As a result, conceptual and problem solving knowledge acquired in school remains largely unintegrated or inert for many students."

A computer-based approach, such as that incorporated in the Hierarchical Analysis Tool, could begin to address this shortcoming, with three additional fringe benefits. First, no major restructuring of current educational practice would be necessary since the problem solving activities that the student would engage in with the hierarchical environment would supplement instruction, rather than supplant it. Second, a computer-based environment would be infinitely more patient and cost-effective than an expert human tutor. Finally, the approach incorporated in the HAT would eliminate a frequent complaint of many novice physics students: "I don't even know how to start the problem." A student using an approach as incorporated in the HAT would always be able to start a problem by considering which principle might be used to solve it.

At this point, it is worth considering how popular a hierarchical concept-based approach to problem solving would be among novices who appear to cherish formulaic approaches. The survey results indicate not only that students are eager to use a concept-based approach to problem solving, but that they also recognize the soundness of this approach. That novices are ready to try a more conceptual approach was even indicated in the survey by several students using the Equation Sorting Tool who stated that having lots of equations available is simply not enough--in addition, they wanted information telling them when and how to apply the formulas. It therefore appears that novices' gravitation toward a formula-based problem solving approach is more of a necessity than it is a choice; they simply do not know of a better method to use. Novices' decision to adopt a formula-based approach is not illogical since equations are indispensable when solving physics problems. However, it is patently evident that formulas are quickly forgotten without a conceptual framework on which they can be cemented.

We may have created the impression that the use of a computer is an essential ingredient in encouraging expert-like behavior in students. This is not the case. There are pedagogical strategies that can be used within a classroom setting both to promote expert-like behavior, and to assess whether or not we are achieving this goal. For example, rather than simply covering the material in the textbook sequentially, we could help students structure their declarative knowledge by highlighting the "big ideas" (such as conservation principles) and by discussing both how ancillary concepts/equations tie into the big ideas, and how the big ideas are related to each other. To combat students' proclivity toward relying on formulaic. approaches to solve problems, we could illustrate that constructing a hierarchical strategy for solving a problem and actually carrying out this strategy by applying equations are two distinctly different processes. This should help students form a dichotomy between general procedures and the specific formulas by which these procedures are instantiated. These two techniques serve to integrate declarative and procedural knowledge.

From the standpoint of assessment, there are methods for evaluating students' progress toward expertise that are more sensitive than homework or test performance. For example, a problem categorization task can be an effective means of assessing whether students are cuing on problems' surface features or whether they are cuing on deep structures. In fact, the categorization task itself can be used as a springboard to discuss how to extract the deep structure from a problem's story line. Asking students to perform qualitative analyses of problems without writing any equations can help us ascertain their ability to combine declarative and procedural knowledge in devising a plan of attack. Further, asking students to provide qualitative explanations of physical situations can help us ascertain the depth of their understanding. The use of students' explanations as an effective assessment instrument is a view that has been espoused in a recent American Journal of Physics editorial.[23]

Finally, it is important to keep in mind that the field of cognitive science, as it pertains to physics learning, is young. The majority of the items listed as references are less than a dozen years old. However, the field appears to have reached a sufficient level of maturity on the research front so that evaluative studies of potential instructional approaches based on cognitive research findings are becoming possible.

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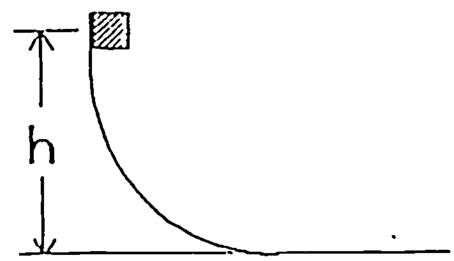
Table 1
Sample Problems Analyzed in Figures 1 and 2
Using the Hierarchical Analysis Tool

PROBLEM 1

A small block of mass M slides along a track having both curved and horizontal sections as shown. The track is frictionless. If the particle is released from rest at height h, what is its speed when it is on the horizontal section of the track?



PROBLEM 2:

A block of mass m is released from rest at height h on a frictionless track having both curved and horizontal sections as shown. When the block reaches the horizontal section, it collides and sticks to another block of mass M. Find the final speed of the two block system.

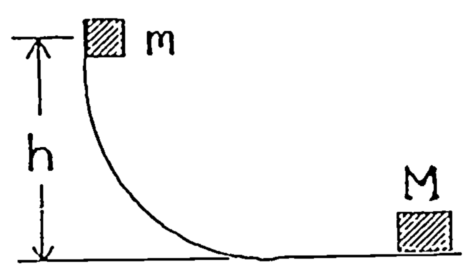


Table 2

Sample Model Problem and Comparison Problems for Categorization Task

Model Problem:

A 2.5 kg ball of radius 4 cm is traveling at 7 m/s on a rough horizontal surface, but not spinning. Some distance later, the ball is rolling without slipping at 5 m/s. How much work was done by friction?

Surface Feature (S) Comparison Problem:

A 3 kg soccer ball of radius 15 cm is initially sliding at 10 m/s without spinning. The ball travels on a rough horizontal surface and eventually rolls without slipping. Find the ball's final velocity.

Deep Structure (D) Comparison Problem:

A small rock of mass 10 g falling vertically hits a very thick layer of snow and penetrates 2 meters before coming to rest. If the rock's speed was 25 m/s just prior to hitting the snow, find the average force exerted on the rock by the snow.

Surface Feature and Deep Structure (SD) Comparison Problem:

A .05 kg billiard ball of radius 2 cm rolls without slipping down an inclined plane. If the billiard ball is initially at rest, what is its speed after it has moved through a vertical distance of .5 m?

No (N) Match Comparison Problem:

A 2 kg projectile is fired with an initial velocity of 1500 m/s at an angle of 30 degrees above the horizontal and height 100 m above the ground. Find the time needed for the projectile to reach the ground.

Table 3

Pre- and Post-Treatment Performance on Categorization Task

Group	Pre-Treatment Performance	Post-Treatment Performance
HAT	56%	66%
EST	61%	61%
T	62%	58%
----	------------	-------------
Total	60%	62%

Table 4

Performance of HAT Group on the Four Item Types

Item Type	Pre-Treatment	Post-Treatment
S-D	17%	34%
S-SD	53%	61%
N-D	67%	76%
N-SD	88%	94%

Table 5

Explanations Task: Pre- and Post-Performance as Measured by LCU

	Group		
	HAT	EST	T
Pre	9.9	17.7	14.4
Post	12.7	7.5	11.4

Table 6

Problem Topics in the Problem Solving Assessment Test

Problem Number	Principle Needed to Solve Problem
1	Newton's Second Law (Statics)
2	Conservation of Linear Momentum
3	Conservation of Energy
4	Conservation of Angular Momentum
5	Conservation of Energy (Applied Twice) and Conservation of Linear Momentum
6	Conservation of Energy and Conservation of Angular Momentum
7	Newton's Second Law (Both Forces and Torques)

Table 7

Pre- and Post-Treatment Performance on Problem Solving Test

Group	Pre-Test	Post-Test
HAT	29.4 (20.1)	41.3 (17.5)
EST	36.4 (25.8)	44.9 (25.9)
T	31.6 (24.6)	44.4 (24.4)

Scores are in per-cent, with standard deviations in parentheses

Table 8

Performance on the 25 Problems Used in Treatment Sessions

Group	Percent Score Principle	Percent Score Answer
HAT	55%	32%
EST	59%	44%
T	59%	42%

Table 9

Results of Exit Questionnaire Administered to HAT and EST Groups

1. During the study, did you have difficulty remembering what you learned in your mechanics course last semester?

	Yes	No
HAT	13	1
EST	11	3

2. How many sessions did it take you to feel comfortable using the computer program?

	1	2	3	4 or 5
HAT	4	6	3	1
EST	7	4	2	1

3. Once you got used to the computer program, what did you think of it in terms of its level of difficulty?

	Easy	About Right	Hard
HAT	9	5	0
EST	8	4	2

4. Did the problems that you solved in the study seem representative of those that you encountered in your physics course?

	Yes	No
HAT	13	1
EST	11	3

5. Would you say that the problems that you solved using the computer were easy, hard, or about right?

	Easy	About Right	Hard
HAT	0	10	3
EST	2	7	5

6. If you had the choice today, would you, a) prefer, b) not prefer, to use the computer program to solve mechanics problems?

	Prefer	Not Prefer
HAT	11	2
EST	8	6

7. Would you have liked having the computer program available to use while you were taking the mechanics course last semester?

	Yes	No
HAT	14	0
EST	10	3

8. Do you think you could solve problems better, a)with, b) without, using the computer program?

	With	Without
HAT	13	0
EST	9	3

9. Do you think your ability to solve problems improved as a result of using the computer program?

	Yes	No
HAT	11	3
EST	6	7

FIGURE 1. Hierarchical Analyzer Menus & Choices for Problem 1

1

Which principle applies to this part of the problem solution?

1. Newton's Second Law or Kinematics
2. Angular Momentum
3. Linear Momentum
4. Work and Energy

Please enter your selection: [4]

(B)ackup (M)ain menu (G)lossary (Q)uit (L)ist selections

2

Describe the system in terms of its mechanical energy

1. Conservative system (conservation of energy)
2. Non-Conservative system (work-energy exchange)

Please enter your selection: [1]

(B)ackup (M)ain menu (G)lossary (Q)uit (L)ist selections

3

Describe the changes in mechanical energy. Consider only the energy of one body at some initial and final state

1. Change in kinetic energy
2. Change in potential energy
3. Change in potential and kinetic energies

Please enter your selection: [3]

(B)ackup (M)ain menu (G)lossary (Q)uit (L)ist selections

4

Describe the changes in kinetic energy

1. Change in translational kinetic energy
2. Change in rotational kinetic energy
3. Change in translational and rotational kinetic energies

Please enter your selection: [1]

(B)ackup (M)ain menu (G)lossary (Q)uit (L)ist selections

5

Describe the boundary conditions

1. No initial translational kinetic energy
2. No final translational kinetic energy
3. Initial and final translational kinetic energies

Please enter your selection: [1]

(B)ackup (M)ain menu (G)lossary (Q)uit (L)ist selections

6

Describe the changes in potential energy

1. Changes in gravitational potential energy
2. Changes in spring potential energy
3. Changes in gravitational and spring potential energies

Please enter your selection: [1]

(B)ackup (M)ain menu (G)lossary (Q)uit (L)ist selections

7

Describe the boundary conditions

1. No initial gravitational potential energy
2. No final gravitational energy
3. Initial and final gravitational energy

Please enter your selection: [2]

(B)ackup (M)ain menu (G)lossary (Q)uit (L)ist selections

8

Is there another body in the system which has not been examined?

1. Yes
2. No

Please enter your selection: [2]

(B)ackup (M)ain menu (G)lossary (Q)uit (L)ist selections

9

The Energy Principle states that the work done on the system by all non-conservative forces is equal to the change in the mechanical energy of the system:

$$W_{nc} = E_f - E_i$$

According to your selections,

$W_{nc} = 0$ (Conservative system: mechanical energy conserved)

$E_f = (\frac{1}{2}Mv^2)_{1f}$

$E_i = (Mgy)_{1i}$

Please press any key to continue

10

*** Work and Energy ***

1. Problem solved
2. Return to Main Menu to continue solution
3. Review previous solution screens

Please enter your selection:

FIGURE 2. Hierarchical Analyzer Menus & Choices
For Second Part of Problem #2

1

Which principle applies to this part of the problem solution?

1. Newton's Second Law or Kinematics
2. Angular Momentum
3. Linear Momentum
4. Work and Energy

Please enter your selection: [3]

(B)ackup (M)ain menu (G)lossary (Q)uit (L)ist selections

2

Describe the system in terms of its linear momentum

1. Momentum conserved (external forces do no work)
2. Momentum not conserved (external force does work)

Please enter your selection: [1]

(B)ackup (M)ain menu (G)lossary (Q)uit (L)ist selections

3

Describe the system at some initial state

1. One particle
2. Two particles
3. More than two particles

Please enter your selection: [2]

(B)ackup (M)ain menu (G)lossary (Q)uit (L)ist selections

4

Describe all motion within the system at some initial state

1. No motion
2. One particle in motion
3. Two particles in motion

Please enter your selection: [2]

(B)ackup (M)ain menu (G)lossary (Q)uit (L)ist selections

5

Describe the system at some final state

1. One particle
2. Two particles
3. More than two particles

Please enter your selection: [1]

(B)ackup (M)ain menu (G)lossary (Q)uit (L)ist selections

6

Describe all motion within the system at some final state

1. No motion
2. One particle in motion

Please enter your selection: [2]

(B)ackup (M)ain menu (G)lossary (Q)uit (L)ist selections

7

The Impulse-momentum theorem states that the impulse delivered to a system is equal to the change in momentum of the system:

$$\int F_{ext}\,dt = P_f - P_i$$

According to <u>your</u> selections,

$\int F_{ext}\,dt = 0$ (conservation of momentum)

$P_i = M_1 V_1,$

$P_f = (M_1 + M_2) V_f$

Please press any key to continue

8

*** Final Menu ***

1. Problem solved
2. Return to Main Menu to continue solution
3. Review previous solution screens

Please enter your selection:

Figure 3

Terms Used for Sorting Equations in the Equation Sorting Tool

---

Physics Terms

acceleration
angular acceleration
angular displacement
angular momentum
angular velocity
center of mass
centripetal acceleration
centripetal force
circular motion
conservation of angular momentum
conservation of energy
conservation of momentum
conservative forces
conservative systems
equilibrium of rigid bodies
frictional force
gravitational force
impulse
impulse & change in momentum
kinematics
kinetic energy
mechanical energy
moment of inertia
moment of inertia (disk)
moment of inertia (hoop)
moment of inertia (rod)
moment of inertia (sphere)
momentum
Newton's Second Law (definition)
Newton's Second Law (dynamics)
nonconservative forces
nonconservative systems
parallel-axis theorem
potential energy
power
rotational dynamics
rotational kinematics
speed
spring force
statics
torque
uniform circular motion
velocity
weight
work
work-energy theorem

Problem Types

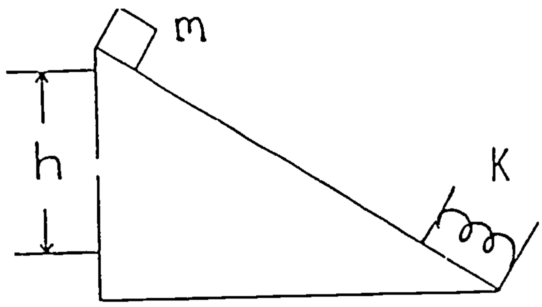
angular motion
Atwood's machine
ballistic pendulum
blocks and planes
circular motion
collisions (elastic)
collisions (completely inelastic)
conveyor belts
energy
equilibrium of rigid bodies
freely falling bodies
friction
frictional forces
gravity
hanging bodies
impulse
inclined planes
kinetic energy
linear motion
motion in a plane
motion in one dimension
potential energy
projectile motion
pulleys
rockets
rolling bodies on planes
rolling without slipping
rotating bodies
springs
statics
strings and ropes
trajectories
uniform circular motion
variable mass
vertical motion
work
work done by friction

Variable Names

acceleration
angie
angular acceleration
angular displacement
angular momentum
angular velocity
arc length
center of mass coordinates
centripetal acceleration
coefficient of kinetic friction
coefficient of static friction
displacement, distance, position
distance, displacement, position
force
friction
gravitational acceleration
height
impulse
kinetic energy
length
mass
mechanical energy
moment of inertia
momentum
normal force
potential energy
position, displacement, distance
power
radial acceleration
radius
speed, velocity
spring constant
tension
time
torque
velocity, speed
weight
work

Figure 4
Explanations Task Items

A block of mass m, initially at rest, slides down a frictionless ramp from a vertical height h onto a light spring of force constant k.



Explain any changes in the behavior of this set-up ...

A1 ...when the block is released from a vertical height of .5h rather than h.

B1 ...if it takes place on the moon rather than on the earth

A2 A block of mass M moves across a smooth floor at velocity v, and then enters a rough region. Explain how increasing the coefficient of friction affects the motion of the block in the rough region.

B2 A bullet of mass m strikes and embeds itself in a block of mass M hanging from a string. Explain any changes in the behavior of the system if it takes place on the moon rather than on earth.