Instructional support for improving students' planning skills to solve Physics problems

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Abstract

Deep analysis on students' cognition (i.e. mental representation in solving physics problem) is crucial to develop tool to support learning. In this paper, we describe a study of how students plan and solve physics introductory mechanics problems. In the study, students were given several physics problems to solve, with varying level of difficulties. For each problem given, students were asked (1) to identify eight categories of information related to the problem (i.e., known / unknown variables, principle, units, just to name a few), (2) to write out (plan) their solution steps, and finally (3) to solve the problem. Findings from the study showed that students' problem solving process indicates that they have partial schema formation. These findings corroborate with the existing theory and claim of students' fragile knowledge, mental representation, and partial schema development. Finally, the computer-based instructional support is discussed based on these findings.

Keywords: Physics problems, Problem solving, Cognition, Mental representations, Schema, Learning Tool

1.0 Introduction

The human mind is seen as a system that processes information through the use of rules and strategies just like a computer (Thomas, 2011). These information processing theories focus on how individuals perceive events, encode information perceived and relate it to existing knowledge in memory. The theories also focus on how new information is stored in memory and retrieved when required. To store and to retrieve information is fundamental to all aspects of cognition. For instance the cognitive processes such as thinking and problem solving rely heavily on the use of previous experience. Nearly everything we do is subject to our capability to recall the past (Groome, 2005). As we perform various activities, we develop structures in our minds to interpret experiences. These structures are developed to allow an easy and efficient access to knowledge when required.

The primary goal of educating physics students is to enable them attain expert competency. But, prior works have identified that physics lessons often do not help students gain the knowledge and skills needed in physics problem solving (McDermott, 2001; Henderson, 2005). It has also been discovered that experts within their domain, have a better structured knowledge, apply a more goal oriented strategy during problem solving and are more metacognitive than novices (Chi et al., 1981; Snyder, 2000; Docktor et al., 2012; Zimmerman, 2006). Taasoobshirazi & Farley (2013) identified the variables that contribute to expertise in physics problem solving and what differentiates experts from novice. These variables include, the problem strategy used; the way problem was categorized; metacognitive strategy (pictorial problem representation) used.

Most research, focused on the individual variables that lead to expertise in physics problem solving (Larkin et al., 1980; Chi et al., 1981; Kohl and Finkelstein, 2008; Docktor et al., 2012). We therefore, focused on the relationship between these variables and how they affect the problem solution. These will help physics instructors to focus on the important variables affecting problem solving success while teaching. Previous works in physics problem solving are reviewed in the next section. The model of physics problem solving adopted is described in Section 3.

2.0 Background: Physics Problem Solving

Problem solving is seen as one of the most significant types of cognitive processing that occurs frequently during learning. Several theorists have considered problem solving to be the main process in learning, mainly in domains such as science and mathematics (Anderson, 1993). A problem could be in several forms such as to locate an object, calculate a solution, answer a question, secure a job etc. The effort taken by an individual to attain a goal, for which the solution is not obvious, is referred to as problem solving. Problems have certain similarities, irrespective of the domain area and complexity. Every problem has an initial state (i.e. the current knowledge of the problem solver) and a goal (i.e. what the problem solver attempts to attain). Often problems require the solver to breakdown the main goal to sub-goals. These sub-goals when effectively mastered results to attaining the major goal. Problem solving requires performing some cognitive activities on the initial state and sub-goals in order to achieve the final goal (Schunk, 2012). Physics is generally regarded as a difficult subject. Existing literature has shown some major differences between experts and novices in terms of physics problem solving. These differences are in their problem solving approach (Larkin et al., 1980), mental representation (Chi et al., 1981) and external representation (Kohl and Finkelstein, 2008). In the next section we will discuss more on the differences between the expert and novice problem solver.

2.1 Novice and Expert Problem Solvers

In an experiment, to solve introductory calculus based physics text problems, Larkin et al. (1980) observed the approach taken by experts and novices. They discovered that the experts use a working-forward approach, which was directed by a good analysis and precise physics representations. The experts achieved this based on their vast experience and structured knowledge of physics principles (Maloney, 2011). Alternatively, the novices used a heuristic approach, because they lacked the required experience and knowledge.

Chi et al. (1981) highlighted the fact that the major difference between a “Novice” and an “Expert” in solving physics problems is in how the problem is represented in memory. Various experiments have shown that “Novice” categorizes physics problems based on the surface content encountered only, while the “Expert” considers not only the surface content but also the underlying principles and concepts (Chi et al., 1981; Hardiman et al., 1989; Blessing et al., 1996; Snyder, 2000; Docktor et al., 2012). Investigations on physics problem representation has proven that “Expert” problem solvers who are able to categorize problems based on principles and concepts are better problem solvers than “Novice” who depend on surface features. The problem solver uses this representation in solving the problem. This makes it a very important process in problem solving. Problem solvers can make good progress if they construct an effective representation (Chu & MacGregor, 2011).

Kohl and Finkelstein (2008) observed that, both novices and experts use external representation when handling physics problems involving, diagrams, graphs and verbal descriptions. However, the two groups differ in how they utilize the external representation. The experts and some intelligent novices spend time making sense of the problem from their free-body diagrams. While it was observed that the novices draw the free-body diagrams based on obligation. In the next section, we discuss on a physics problem solving model.

2.2 Model of Physics Problem Solving

In our current study, we analysed three main physics problem solving components, namely categorization skills, use of strategy, and free-body diagrams. This is similar to the structural equation modelling used by Taasoobshirazi & Carr (2009). Our goal is to determine how these key components affect students’ success in solving physics problems. The scoring for the various components identified is explained as follows:

- **Use of Strategy -** The student’s strategies were evaluated based on either working-forward or working-backward. Typically students start by writing equations that involve the given or desired quantities in the problem statement and then work backwards. While a proficient solver think of the appropriate physics concept and devise a plan, which leads to working forward from the given information to the desired solution. For example considering a problem for which the goal is to find the final velocity of a block when it reaches the end of an inclined plane. An expert will approach the problem by first noting the motion of the block along the slope considering frictional force and gravity. That will lead to the equation F=ma (force = mass x acceleration). That equation in turn leads to an equation relating the final velocity, which is the goal. But novices begin by focusing on the goal of finding the final velocity. Students received zero points for using the working-backward strategy and one point for using the working-forward strategy.

- **Free-Body Diagram -** The quality of student's free-body diagrams was also scored. This was done by comparing the diagrams to a defined sketch for each problem. The defined sketches had all the factors which represent a complete diagram. For example a complete sketch for the first problem included the weight of the object, the spring or spring constant and the extension of the spring for a single spring and two similar springs in parallel. While in the second problem, a complete sketch included the force acting on a trolley and its velocity. Students received one point for each main factor pictorially represented.

- **Categorization Skills -** Students ability to identify the relevant features within the problem such as known, unknown, objects, problem domain, principle and any related concept, was graded. One mark was awarded to any correct data identified within the problem. Note that the definition of categorization skill in our study is somewhat differ from the study conducted by Taasoobshirazi & Farley (2013).

- **Problem Solution -** The students' problem-solution was scored based on their ability to use the right equation and produce the right answer. To determine the equation score, the students' answers were given one point if all the correct equations needed to solve the problem are provided and zero if a wrong equation is used. Similarly, for the students' were awarded one point for a correct answer when the right equation was used and zero points for incorrect answers. However, if the equation is correct and a simple calculation error occurred, full credit was still given for the problem.

3.0 A study on students' plan and solution of Physics problems

An experiment was carried out to determine how students plan and solve physics problems. The main aim is to test the effect of the students' categorization skills, use of strategy and quality of free-body diagrams, on their final solution. The objectives are two-fold: (1) To understand students' mental representation during physics problem solving, (2) To propose computer-based instructional support, i.e. the Planning module.

3.1 Participants

The participants in this experiment were 37 pre-university students from Centre of Science Foundation, of the University of Malaya. The students are enrolled in the physical major and biological science major. The experiment was conducted at the beginning of the second semester, after offering introductory courses in mechanics, measurement, optics and waves.

3.2 Procedure and materials

The students were given 8 problems from various domains in introductory mechanics together with necessary worksheets. The problems were grouped into 2 sets of 4 problems. The problems, with varying level of difficulties are explained in Table 1. The students started by attempting questions in Set 1. A break of 15 minutes was given, before they attempted the questions in Set 2. For each problem, students were instructed, (1) to identify 8 categories of information related to the problem -- known/unknown variables, principle(s), objects, units, and problem domain (2) to write out (plan) their solution steps and to draw a free-body diagram, and finally (3) to solve the problem.

Table 1: Varying level of difficulties between problems in Set 1 and Set 2

Set 1	Similarities and Differences	Set 2
A1	Identical problems Same Unknown	A2
B1	Less identical than between A1 and A2 Same principle but different equation	B2
C1	Less identical than between B1 and B2 Same sub-domain but different principle	C2
D1	Less identical than between C1 and C2 Different domains	D2

3.3 Results and discussion

The analysis of the Mann-Whitney U test was conducted, which aimed at comparing differences in the scores between students who used backward strategy and students who used forward strategy. A Bonferroni adjustment to the alpha value of .05 (i.e. divided by the number of comparisons made) was used for the analysis. As an effect size measure (for non-parametric test), we used the effect size *r*, that is, values of .1 indicate small effect, .3 indicate medium effect, .5 indicate large effect (Cohen, 1988).

As previously described in Section 2.2., the variables and outcome measures are categorization scores, free-body diagram scores, and problem solution scores. Note that, the strategy scores were used as categorical variable to categorized post-hoc students into two groups, namely backward strategy group and backward strategy group.

In this paper, the analysis of results was discussed for problem B2 and C2 only. Roughly speaking, 76% to 97% of students used forward strategy to solve various problems. This is to no surprise, given that these students have completed one semester and thus have sufficient knowledge on physics mechanics prior to the experiment. Therefore, it is almost impossible to run statistical analysis to compare between the two strategy groups. Moreover, the mean for the problem solution scores for these two problems are too obvious to be considered for further analysis.

Table 2: Mean and standard deviation

	Backward strategy			*Forward strategy*		
	n	*M*	*SD*	*n*	*M*	*SD*
Problem B2						
Categorisation	21	5.86	1.74	16	6.44	1.21
Free-body diagram	21	0.62	0.87	16	0.50	0.97
Problem solution	21	0.14	0.48	16	2.00	1.51
Problem C2						
Categorisation	27	7.70	2.40	10	8.60	1.58
Free-body diagram	27	0.56	0.85	10	0.20	0.63
Problem solution	27	0.19	0.40	10	1.90	0.32

Note for Table 2: Categorization score (ranging from 0 to 12, depending on the problem); free-body diagram score (a complete sketch that include factors needed for inclusive diagram, ranging from 0 to 4, depending on the problem); strategy score (0 for backward strategy, 1 for forward strategy); solution score (ranging from 0 to 4, depending on the problem).

Table 3: Mann-Whitney U test of the scores of the students who used backward strategy and the students who used forward strategy for the two problems

	U-test
Problem B2	
Categorisation	$U = 141.50, p = .40, r = -.14$
Free-body diagram	$U = 150.50, p = .52, r = -.11$
Problem solution	**$U = 50.50, p = .000, r = -.68$**
Problem C2	
Categorisation	$U = 101.50, p = .25, r = -.19$
Free-body diagram	$U = 105.00, p = .19, r = -.22$
Problem solution	**$U = 2.50, p = .000, r = -.85$**

Table 2 shows the mean and standard deviation of students' score for the categorization skill, free-body diagram quality, and solution accuracy for problem B2 and problem C2 according to the strategy used. The forward strategy group showed higher mean for the solution scores compared to the backward strategy group. For problem B2, the mean for the solution score was 0.14 and 2.00 for the backward and forward strategy group, respectively. For problem C2, the mean for the solution score for the backward strategy group was 0.19 while the mean for the forward strategy group was 1.90. Another interesting result is that the forward strategy group also showed higher mean categorization score than the backward strategy group for both B2 and C2. However, their mean free-body diagram score was lower than the backward strategy group for both problems.

Table 3 shows the results of the Mann-Whitney U Test. The results showed no significant differences (between students who used forward strategy and students who used backward strategy) in the categorization score and free-body diagram score for both B2 and C2. Interestingly, the results of the Mann-Whitney U test revealed significant difference in the problem solution score (for B2) of those who used forward strategy and those who used backward strategy, with large effect size, U = 50.50, z = -4.15, p =.000, r = -.68. Similarly, there was a significant difference (with large effect size) in the problem solution score for C2, U = 2.50, z = -5.16, p =.000, r = -.85.

Those who used forward strategy exhibited the strategy used by experts by first thinking about the physics concepts or principles in devising their solution plan instead of immediately delving into the equation involving the givens in the problem. The use of such strategy leads to better categorization of information and solution. This study corroborates other studies that show physics experts are better problem solvers due to their deep structure knowledge compared to novices who typically rely on the surface structure of the problem. Much to our surprise, students who used forward strategy did not fully utilize external representation such as free-body to visualize the problem. This is contradicted to the study conducted by Kohl & Finkelstein (2008) who revealed that successful problem solver and expert-alike often utilize external representations when solving physics problems. Additionally, not much has been reported on the relationship between these two strategies and free-body diagrams in physics problem solving. Hence further investigation is needed.

4.0 Computer-based instructional support for *planning* to Physics problem

Based on the results of the analysis (as previously discussed in Section 3.3), we propose a computer-based instructional support tool. The tool focuses on a cognitive approach to learning, which deals with the mental processes involved in acquiring skills to solve physics problems. It is hoped that this tool able to help students to gradually instil a metacognitive planning (Taasoobshirazi and Farley, 2013) when solving physics problems and eventually towards working-forward strategy.

4.1 Planning module

One of the most important components of problem solving is planning. This stage involves drawing pictorial representations of the problem, identifying the correct principle and equations. Typically, during problem solving, a problem solver draws free-body diagrams to indicate the main variables and their interactions. Making these pictorial representations at the beginning helps the solver determine which approach and principles are appropriate in solving the problem. After identifying the relevant principles, the solver can determine which equation is appropriate in solving the problem. The planning module allows the solver to implement this approach seamlessly. In this module, problem solvers are also guided with similar worked examples, when they encounter difficulties.

The planning module allows a problem solver to plan and develop a solution in three steps. The first step involves drawing a free-body diagram as shown in Figure 1. This allows the solver to have a pictorial representation of the problem. With the aid of this representation, the solver finds it easier to identify the principles and equation required to solve the problem. In the second step, the solver identifies the principle and equations required to solve the problem from drop-down tree of principles and equations as seen in Figure 2.

After selecting the appropriate principle and equations, the solver moves to the final step where the variables are substituted into the equations. The final result is then calculated as shown in Figure 3

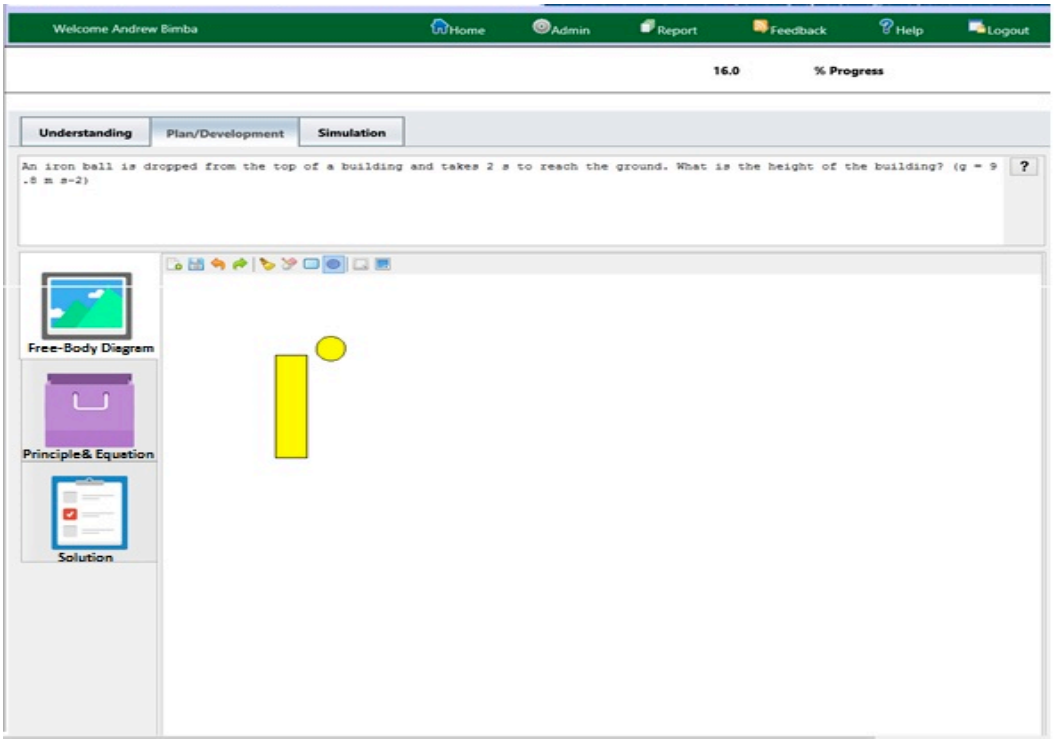

Figure 1: Free-Body diagram for the Planning

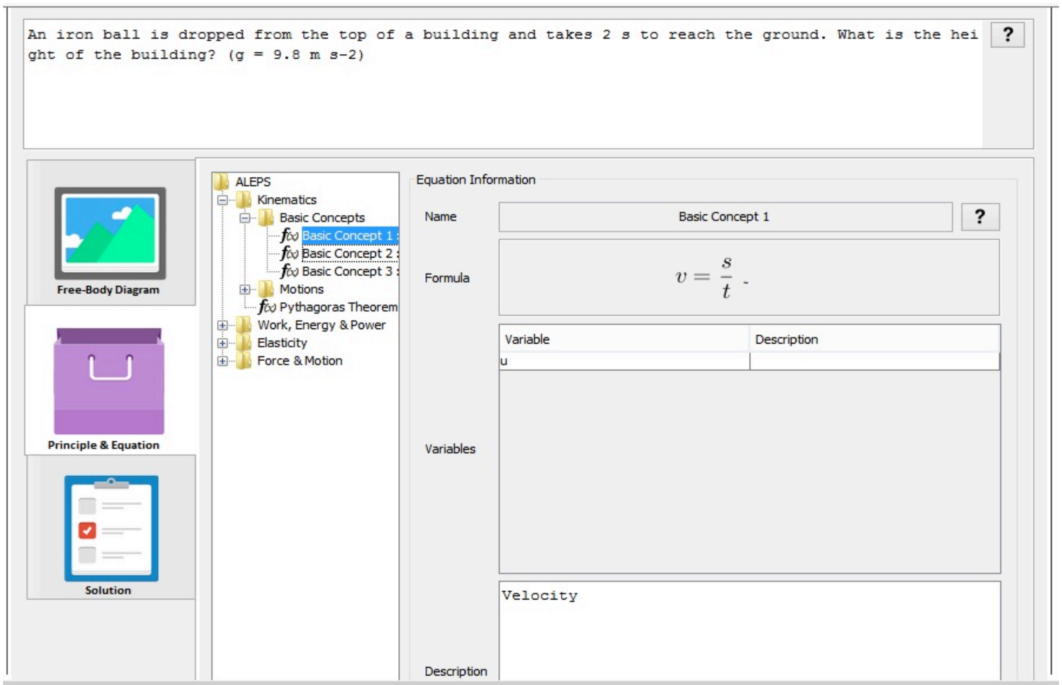

Figure 2: Drop-down tree of principles and equations for the Planning module

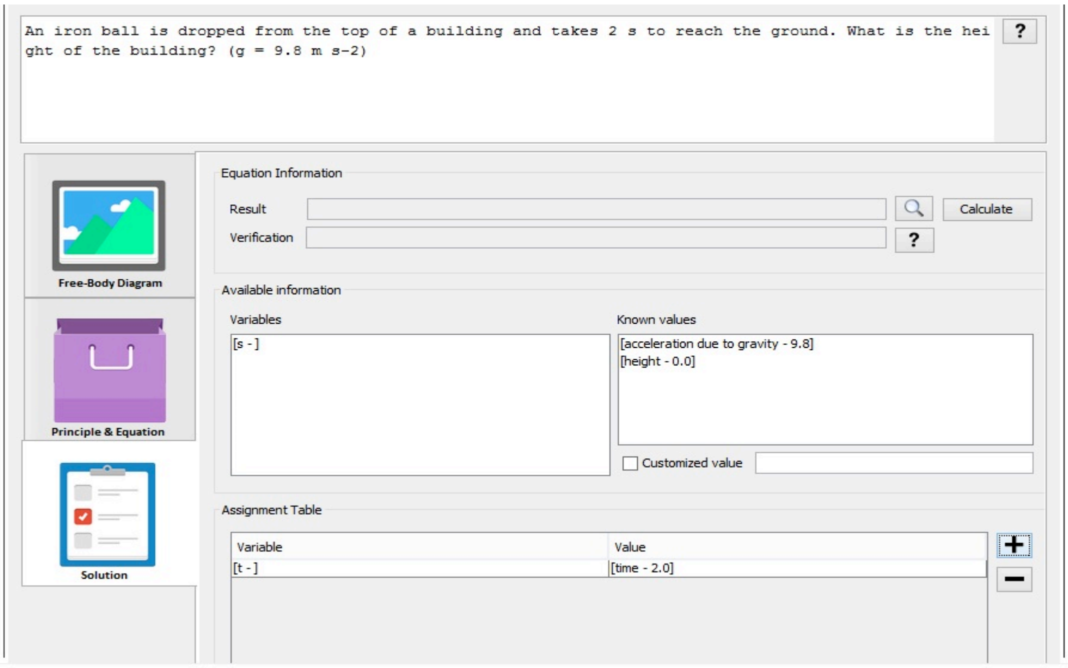

Figure 3: Solution for the Planning module

For example, consider the following sample question:

A workman pushes a carton of mass 50 kg up an inclined plane into a lorry. The inclined plane makes an angle of 45^o with the horizontal floor and the frictional force between the inclined plane and the carton is 135 N. If the workman pushes the cartoon with a force of 500N, what is the acceleration of the carton?

The solver is able to draw a pictorial representation (i.e. free-body diagram) of the problem as seen in Figure 4. With this free-body diagram, the solver is able to visualize the forces acting on the carton and the effect of the inclined plane. With this, the solver can easily identify Newton's second law and trigonometry as the principle involved in approaching a solution. Then, the appropriate equations can be applied on the principle identified. Based on Newton's second law, (the acceleration a of a body is parallel and directly proportional to the net force F acting on the body, is in the direction of the net force, and is inversely proportional to the mass m of the body, i.e., F = ma) the force acting on carton (its weight) is calculated using the formula "W=mg" where W is the weight of the cartoon, m is the mass of the cartoon and g is the acceleration of the body due to gravity (10m/s). Using trigonometry, the formula based on sine rule is used to resolve the force due to the weight of the carton W sinΘ. The resultant force is then calculated by resolving all the forces acting parallel to the carton (Fr= W sinΘ + fr - f). Finally the acceleration of the carton is calculated using formula from Newton's second law (F = ma); a=F/m. The final output is a mental representation of the solution which comprises of the geometric representation and derived values from the solution.

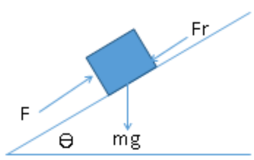

Figure 4: Free-Body Diagram

5.0 Conclusion

This paper has presented a study of how students plan and solve physics introductory mechanics problems. Findings from this study corroborate existing studies, which indicate the fragility of physics knowledge and partial schema development among students. Results of this study also revealed important implications for physics teaching in a similar vein with the study of Taasoobshirazi & Farley (2013). That is to say, several important factors affecting problem solving success namely, the ability to identify relevant problem features, the quality of a free-body diagram, and the strategy use. Finally, this paper concludes with computer-based instructional support called the Planning module aimed to provide students with better planning to physics problem solving.

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