Implications of Cognitive Studies for Teaching Physics Problem-Solving: A Review

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A growing body of research literature on physics problem-solving can provide us a significant guidance on effective instructional strategies. In this article is presented a brief review of research on physics problem-solving and some necessary prerequisites are discussed along with students' difficulties in physics problem-solving. Some effective teaching strategies for physics problem-solving presented that can be useful for physics education researchers and physics teachers.

Keywords: Physics, Problem-solving, Teaching strategies, Cognitive abilities, Students' difficulties

Introduction

Problem-solving is considered to be one of the most important skills learned in physics courses (Redish & Steinberg, 1999; Van Heuvelen, 2001). Therefore, dealing with physics problem-solving is one of the areas of increasing importance in cognitive research and its implications for physics teaching. In this brief review, the implications of cognitive studies for teaching and learning of physics problem-solving are discussed and a student-centred approach for physics problem-solving is suggested. An attempt is made to address the following three sets of interrelated questions, based on cognitive studies:

- What is involved in effective physics problem-solving? What cognitive abilities are required for physics problem-solving?
- What do students bring to physics problem-solving class? What are their main cognitive and metacognitive difficulties?
- What are the effective teaching strategies for physical problem-solving?

Some Cognitive Abilities Required for Physics Problem-Solving

In this section, some necessary prerequisites for efficient physics problem-solving are discussed.

An understanding of physics concepts and principles: Physics concepts and principles are used for conceptual representations of physical systems, events and processes. Clearly, a good understanding of physics concepts and principles is a prerequisite for expert problem-solving (Mestre, 1994; Redish & Steinberg, 1999; Reif, 1986, 1995a).

Effective description of knowledge using multiple representations: Instead of thinking of a physics problem to determine some unknown quantity, we can think of the problem statement as describing a physical process. A physicist uses qualitative analysis and various representations to understand a physical process. A physical process may be described using different representations, e.g. words, pictures, diagrams, graphs, maps or mathematical symbols, with different degrees of precision (Larkin, 1981; Reif, 1995a; Van Heuvelen, 1991).

This requires a number of thinking processes such as translating symbols in words, describing physical processes in words, interpreting a mathematical relation, interpreting a graph, use of system schema, motion maps, force diagrams, energy diagrams, electric circuit diagrams, etc. (Arons, 1997; Hestenes, 1987). Developing mathematical reasoning is one of the top requirements of physics problem-solving. This includes a number of thinking/reasoning processes such as proportional reasoning, coupling arithmetical/algebraic reasoning to graphical representation, scaling and functional reasoning, reasoning related to derivation and integration, etc. (Arons, 1997).

Making of appropriate assumptions, construction and application of conceptual models: Effective knowledge of modeling and assumptions is of great importance in solving physics problems, including many real-world problems (Bolton & Ross, 1997; Fortus, 2009; Hestenes, 1992). According to Hestenes (1987), an expert attacks a physics problem by first constructing an abstract conceptual model from the given information in the problem and then applying the model to find desired results. Students need to know clearly the descriptive variables representing properties of an object or a system, the equations of the model which describe structure and time evolution of the object or system and equations of constraints, etc.

Effective knowledge organization and access: Physics experts organize their knowledge in a highly coherent form which is easy to remember and accessible (Mestre, 1994; Reif, 1995a; Van Heuvelen, 1991). What is important is not only what physics knowledge students have but how they organize it and under what circumstances they elicit it (Reif, 1986; Sabella & Redish, 2007). This leads to the metacognitive abilities discussed below.

Metacognitive abilities: An important role is played by metacognition in physics problem-solving. To become an expert in physics problem-solving one has to acquire strategic knowledge of when to apply what basic concepts and principles and how to apply them (Gunstone & Mitchel, 1998; Larkin, 1981; Sabella & Redish, 2007). One has to pay deliberate attention to maintain coherent evocations corresponding to the scientific conceptual formulations of the physical world. For example, the concept of force can become well established in the mind of the student with his/her deliberate attention, under active monitoring of a teacher, with multiple exposures over extended time periods in a variety of contexts (Hammer, Elby, Scherr, & Redish, 2005).

Students' Difficulties in Physics Problem-Solving

Many physics students enter classes with strongly held preconceptions which are often misconceptions (McDermott & Redish, 1999). These students' major problem-solving difficulties are related to interpretation of basic physics concepts and principles (Reif, 1987). Many physics teachers use diagrams, such as free body diagrams in mechanics, and other qualitative representations, as examples for students. However, studies show that one of the greatest difficulties for many students is that they use formula-centred problem-solving methods and do not use qualitative representations, such as diagrams, graphs etc. (Hestenes, 1987; Larkin, McDermott, Simon, & Simon, 1980; Van Heuvelen, 1991).

Several studies reveal that experts and novices organize and access their knowledge in different ways (Bagno & Eylon, 1997; Chi, Lewis, Reimann, & Glaser 1989; Fuller, 1982; Larkin et al., 1980; Reif, 1995a; Sabella & Redish, 2007; Van Heuvelen 1991). Proficient problem solvers or experts organize their knowledge in a richly interconnected hierarchical network of knowledge units called "chunks" and it is globally coherent for problem-solving tasks. Novices' knowledge is often quite incoherent or characterized by a local rather than a global coherence, with inconsistency and isolation from other appropriate and related knowledge structures. When given a physics problem, they identify some superficial structural feature described in the problem, such as a rope, a spring, an inclined plane etc. They then search randomly for and wrongly use formula linked with that feature. Due to these characteristics students find it difficult when they attempt to solve complex and challenging problems (Larkin et al., 1980; Mestre, 1994; Reif 1995a; Van Heuvelen, 1991). In addition to this, the finite capacity of working memory is one of the most serious limitations on problem-solving. Note that the working memory has capacity of 5 to 7 items or chunks (Hestenes, 1979; Larkin et al., 1980).

In addition to the above mentioned cognitive difficulties and limitation of the working memory, students face metacognitive difficulties, and difficulties related to "cognitive attitudes" or expectations (Gunstone & Mitchel, 1998; Redish & Steinberg, 1999). They approach the learning of physics with unfavourable attitudes toward physics learning and physics problem-solving (Redish & Steinberg, 1999).

Effective Teaching Strategies for Physics Problem-Solving

The growing literature on cognitive studies related to physics problem-solving can provide us a significant guidance on effective instructional strategies. Considering the student-centred approach, any effective method for physics problem-solving needs to deal with the necessary prerequisites for physics problem-solving and the major problem-solving difficulties of students mentioned in previous sections (in fact, they are related). First, development of necessary cognitive abilities for problem-solving is discussed.

The physics concepts and principles must be specified without ambiguity and with precision and generality. A particular physics concept may be interpreted in various possible ways. The physics teacher must know what are some of the advantages and disadvantages of each mode of concept interpretation (Reif, 1987). For example, the concept of acceleration can be specified explicitly using its operational definition, following 5 major steps (Reif, 1986). A procedural approach to construct Gaussian surface and Amperian loop (Yadav, 2004) can be of great help to students to solve problems in electromagnetism. Cognitive research findings show that concept interpretation can be very fast if one has already got sufficient exposure in different contexts and has a sufficient knowledge about various cases of a concept (Mestre, 2001; Reif, 1987, 1995a). "ConcepTests" (i.e. concept tests) from *Peer Instruction* (Mazur, 1997) and "Checkpoints" and "Questions" from *Fundamentals of Physics* (Halliday, Resnick, & Walker, 1997) can be of great help to students to improve their introductory physics concepts and principles.

If a physics student possesses a misconception, some changes are required in existing knowledge for effective learning. Mestre (1994) suggested a systematic approach for helping students overcome misconceptions. The various steps of this approach are listed below: 1. Probe for misconception, 2. Ask questions to clarify students' views, 3. Suggest some events that can create conceptual conflict with students' alternative concepts, 4. Encourage dialogue and debate, 5. Guide students toward developing correct physics concept, and 6. Re-evaluate students' understanding. Note that the third step is very important as it develops cognitive conflict or disequilibrium, which is the principal requirement in initiating the accommodation (Fuller, Karplus, & Lawson, 1977).

A physics teacher must encourage the students to represent the physical processes or events in various ways, words, pictorial representation, physical representation, mathematical representation, etc (Van Heuvelen, 1991). For example, the equation of motion $\acute{\imath} = \acute{\imath}_0 + at$ can be described using a table, a graph, a motion diagram and words, in addition to the mathematical representation (Yadav, 2005). One must consider the purpose behind the use of available representations and choose them in such a way that the performance of the tasks of interest will be facilitated in a good way (Kohl & Finkelstein, 2008; Reif, 1995a).

The physics instruction must provide opportunities for students to see that a small number of concepts are the basis for many diverse applications. The teacher must provide opportunities to students to organize and learn to access conceptual knowledge in some sort of organized structures, e.g. hierarchical charts, concept-map diagrams, etc. (Mestre, 1994; Reif 1995a; Sabella & Redish, 2007; Van Heuvelen, 1991, 2001). For example, the concept-map diagram of electromagnetism is helpful for students to learn how different concepts, principles and laws of electromagnetism are related to Maxwell's equations and Lorentz force law (Yadav, 2004).

Several authors have suggested various systematic approaches for physics problem-solving in different contexts (Bolton & Ross, 1997; Dufresne, Gerace, & Leonard, 1997; Hestenes, 1987; Leonard, Dufresne, & Mestre, 1996; Reif, 1981; Van Ausdal, 1988; Van Heuvelen, 1991; Wright and Williams, 1986). Following these studies, the major steps which can be used for a systematic problem-solving method are presented.

Initial qualitative analysis of a problem: Analysis of a physics problem is of great help to find its solution. The students must be able to clearly specify a problem by describing the physical situation and by summarizing its goal. The physics teacher should encourage the students to change the word description into other representations, viz. diagrams, graphs, motion maps, etc. He/she must encourage the students to reason qualitatively about the physical process and to describe the situation in terms of more technical physics concepts, e.g. acceleration, force, velocity, torque etc. (Bolton & Ross, 1997; Dufresne et al., 1997; Hestenes, 1987; Larkin, 1981; Reif, 1995a; Resnick, 1983; Van Heuvelen, 1991). Therefore the ability to use multiple representations is of great importance in facilitating the initial analysis of the problem.

Actual construction of a solution: An effective strategy for finding the solution of a problem is to decompose the solution process into simpler and manageable sub-processes (Reif, 1995a). One must repeatedly decide what to do, what particular principle one has to choose to apply in a particular situation. Therefore, an effective organization of knowledge is of great importance in facilitating the decisions needed for problem-solving. The implementation of the decision is greatly helped by the abilities of interpretation of the concepts and description of knowledge (Reif, 1981, 1995a; Van Heuvelen, 1991). Skills of making appropriate assumptions and conceptual modeling have positive impact on improving students' physics problem-solving ability (Fortus, 2009; Hestenes, 1987).

Evaluation of the solution: It is important to check the solution to assess whether it is correct and satisfactory and to revise if need be. Some important checks are listed below: 1. Whether different representations used to solve the problem are consistent? 2. Whether goals are attained? 3. Whether the solution is self-consistent? 4. Whether the equations are dimensionally correct? 5. Whether the solution is correct in limiting cases (Bolton & Ross, 1997; Hestenes, 1987; Reif, 1995a; Wright & Williams, 1986).

Critical reflection and refinement: Reflective thinking is essential for mastering the physics problem-solving skills. According to Hestenes (1992), 'post-mortem analysis', i.e. critical reflection after finding the solution, is the deepest learning in physics problem-solving. One can ask several questions after solving the problem. Hestenes (1992) has provided a list of questions, such as: 'What was the key to the solution? Can the argument be simplified? Are there other ways to solve the problem? Which is the best? Can the problem and solution be generalized?'

A physics teacher must encourage students to be self-reflective about their own learning and to test their own thinking and reasoning processes for internal consistency (Arons, 1997; Mestre, 2001). Studies show that good learners show metacognition in classroom (Gunstone & Mitchel, 1998). Their studies show that metacognitive knowledge, awareness and control can be promoted with appropriate learning experiences. Considering the finite capacity of working memory, its control is an essential requirement of any efficient and effective problem-solving strategy. Therefore, teachers should teach their students how to use notebooks, paper and pen in an effective way to monitor their reasoning processes, during physics problem-solving (Hestenes, 1979; Larkin et al., 1980). To become an expert in problem-solving skills, one has to get multiple exposures over extended time periods in a variety of contexts (Larkin et al., 1980; Mestre, 2001; Van Heuvelen, 2001). The physics teacher must provide sufficient opportunities for students to be active participants during class in constructing physics concepts, using the concepts and multiple representations in solving physics problems.

Some micro-teaching lessons (teaching short lessons) related to interpretation of physics concepts, multiple representations, organization of physics knowledge, etc. can help pre-service physics teachers to get experience of teaching these important abilities (Yadav, 2005). Pre-service physics teachers must be taught explicitly how to teach physics problem-solving. Teaching of some lessons related to physics problem-solving must be part of assessment of pre-service physics teachers.

Several independent studies suggest that the students following the inquiry-based, interactive-engagement methods performed significantly better on problem-solving tasks than the students in traditional introductory courses (Hake, 1998; Redish & Steinberg, 1999; Thacker, Kim, & Trefz, 1994). Some studies (Harskamp & Ding, 2006; Heller & Hollabaugh, 1992; Heller, Keith, & Anderson, 1992; Tao, 2001) show that co-operative group learning has positive effects on physics problem-solving performance.

Physics teachers should use physics education research findings to improve their instructions. There is a need to produce and/or have access to good instructional materials which address cognitive issues discussed in this paper. Van Heuvelen (1991) developed a method of instruction that uses a set of sheets called *Active Learning Problem Sheets* (the *ALPS* kit). There are some instructional materials which are very helpful to develop concepts and principles of physics and problem solving ability, for example, *Teaching Introductory Physics* (Arons, 1997), *Understanding Basic Mechanics, Text and Workbook* (Reif, 1995b), *Peer Instruction, A User's Manual* (Mazur, 1997), *Six Ideas That Shaped Physics* (Moore, 1998), etc.

Mestre (1994) suggests that the student assessments should reflect more closely the types of problems and conceptual questions that physicists consider when they do physics. One study showed that many physics students did not overcome conceptual difficulties even after solving 1500 traditional physics problems (Kim & Pak, 2002). Therefore, to test conceptual understanding and higher-level thinking, exercises that can be solved simply by using standard formulas and inserting numerical values should be avoided. Sabella and Redish (2007) suggest that physics exams should be designed to help students develop explicit links to related topics in the physics courses and link their qualitative understanding to quantitative problem-solving so that they can acquire sufficient skills in physics problem-solving. Formative assessment should be used frequently to monitor students' understanding of physics concepts and their problem-solving skills (Mestre, 2001).

Summary

In this article the importance of cognitive studies and their implications for teaching and learning physics problem-solving are discussed. An understanding of physics concepts and principles, description of knowledge, organization of knowledge, making assumptions and modeling, some thinking/reasoning processes and metacognitive abilities are necessary prerequisites for efficient physics problem-solving. Many physics students enter classes with misconceptions and others use formula-centred problem-solving methods and do not use qualitative representations, such as diagrams, graphs etc. Students' knowledge is often quite incoherent, fragmented and unorganized. Many students also have metacognitive difficulties.

To help students, the interpretation of the physics concepts and principles must be taught explicitly. Qualitative reasoning based on physics concepts and principles must be encouraged. Students must be helped to develop qualitative and quantitative reasoning and problem-solving skills, and helped to use multiple representations to analyze the problem and construct its solution. Students also need help to organize their physics knowledge, using hierarchical charts, concept maps, etc. The physics teacher should teach a systematic problem-solving method explicitly. He/she should teach metacognitive strategies to his/her students. The physics teacher should encourage the students to become active participants during physics problem-solving sessions. Studies show that inquiry-based, interactive engagement and collaborative methods have positive effects on physics problem-solving. To get expertise in physics concepts and problem-solving skills, students should get multiple exposures over extended time periods in a variety of contexts.

Teaching of some lessons related to physics problem-solving must be part of assessment of pre-service physics teachers. Physics teachers should use physics education research findings to improve their instructions. Conceptual questions and advanced problems must be the part of the student assessment and formative assessment should be used frequently to monitor students' understanding of physics concepts and their problem-solving skills.

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