Enhancing Cognitive Development through Physics Problem Solving: A Taxonomy of Introductory Physics Problems

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Abstract. As part of an ongoing project to reform the introductory algebra-based physics courses at George Washington University, we are developing a taxonomy of introductory physics problems (TIPP) that establishes a connection between the physics problems, the type of physics knowledge they involve and the cognitive processes they develop in students. This taxonomy will provide, besides an algorithm for classifying physics problems, an organized and relatively easy-to-use database of physics problems that contains the majority of already created text-based and research-based types of problems. In addition, this taxonomy will reveal the kinds of physics problems that are still lacking and that are found to be necessary to enhance students' cognitive development. For this reason, we expect it to be a valuable teaching resource for physics instructors which will enable them to select the problems used in their curricular materials based on the specifics of their students' cognition and the learning objectives they want to achieve in their class. This organization scheme will also provide a framework for creating physics-related assessments with a cognitive component.

Keywords: physics problem solving, taxonomy, physics problems, physics education research.
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INTRODUCTION

Developing proficiency in problem solving has long been recognized as one of the primary educational objectives in introductory science courses. Current educational requirements indicate that introductory science courses in particular should emphasize skill building in quantitative and qualitative problem solving along with developing a knowledge base [1, 2]. Yet research in the cognitive sciences over the years has revealed the complex and dynamic character of the problem-solving process [3-10]. Forty years of research in expert-novice problem-solving behavior have elucidated specific characteristics of the thinking processes of the two categories of learners [11]. In parallel, physics problem developers have made efforts to create physics problems that move the novices towards a more expert-like status [12-16]. Moreover, there are currently successful models that describe different aspects of the thinking process that takes place during physics problem solving [17, 18].

This project proposes to create a taxonomy of introductory physics problems (TIPP) that organizes physics problems according to the manner in which disciplinary knowledge is processed within a learner's cognitive system. The desired outcome is expected to be in good agreement with existing novice-expert research as well as modern models of students' thinking.

By problem solving we mean "cognitive processing directed at achieving a goal when no solution method is obvious to the problem solver" [19, 20]. We adhere to the characterization of the problem-solving process proposed by Mayer and Wittrock [5]: "Problem solving is cognitive, that is, it occurs internally within the problem solver's cognitive system and can only be inferred indirectly from the problem solver's behavior. Second, problem solving is a process, that is, it involves representing and manipulating the knowledge in the problem solver's cognitive system. Third, problem solving is directed, that is, the problem solver's cognitive processing is guided by the problem solver's goals. Fourth, problem solving is personal, that is, the individual knowledge and skills of the problem solver help determine the difficulty or ease with which obstacles to solutions can be overcome."

METHODOLOGY

TIPP is substantially based on the taxonomy of educational objectives developed by Marzano [21]. Fig. 1 shows schematically the theoretical inputs that influence TIPP. According to Marzano's model of behavior, the mental activity that humans perform is the result of the interaction of three mental systems: the self-system (which decides to engage or not in a certain task), the meta-cognitive system (which sets goals and strategies) and the cognitive system (which processes the relevant knowledge). It is well known

that what students believe about physics as a science and what they expect from their physics courses determine their attitude and motivation towards the process of learning physics. Ultimately, those factors influence their overall achievement in a physics course. For the purpose of this project we will restrict ourselves to the cognitive system and not include the meta-cognitive aspects in our taxonomy.

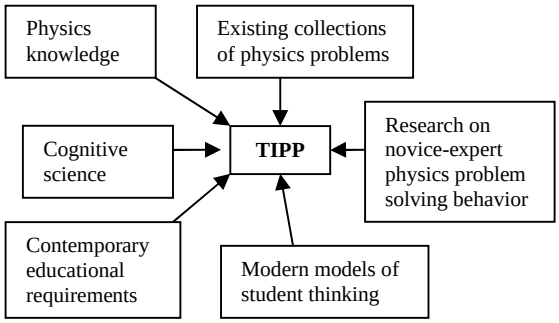


FIGURE 1. The theoretical basis of the Taxonomy of Introductory Physics Problems (TIPP).

While developing TIPP we address the following questions: *Can physics problems be categorized according to cognitive processes and knowledge domains? What is the relationship between physics problems, knowledge domains and cognitive processes? Are there cognitive processes that are not activated by the existing physics problems?* Following Marzano's taxonomy [21], we have developed an algorithm to organize physics problems according to a two-dimensional scheme. The first dimension of TIPP refers to the *knowledge domain* that is involved in a certain problem while the second deals with the *cognitive processes* that a solver needs to perform in order to solve it. These two dimensions are fundamentally different. The *knowledge domains* encountered in physics problems are referred to: *declarative knowledge* or *information* and *procedural knowledge* or *mental procedures*. The *cognitive processes* required to solve physics problems are: *retrieval, comprehension, and analysis* and *knowledge utilization.* Fig. 2 provides succinct descriptions of these complex cognitive processes, their component processes and how they act on different types of knowledge. All of the cognitive processes operate in the same manner on both types of knowledge, with the one exception of *retrieval* — this acts on information differently than on mental procedures (as shown in Fig. 2). These four cognitive processes are hierarchical relative to the level of consciousness required to control their execution [21].

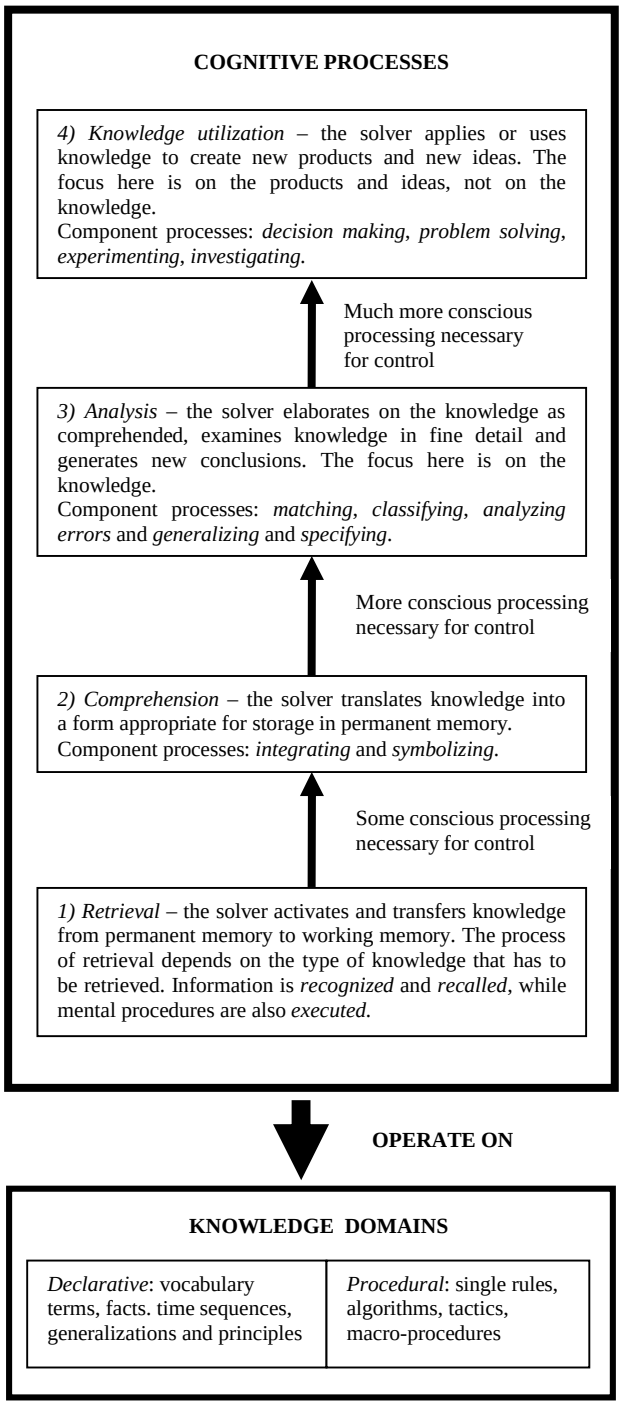


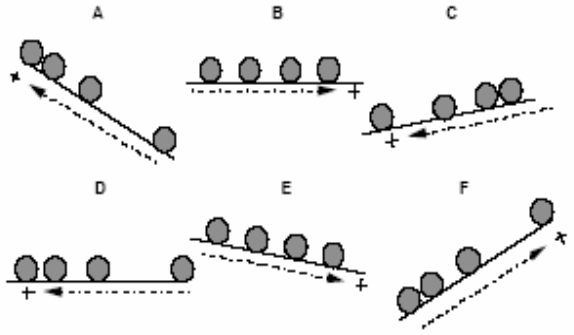
FIGURE 2. The cognitive processing of knowledge according to Marzano [21].

How do we label a physics problem?

To characterize an individual physics problem, we have defined the following parameters:

- the *type of knowledge* involved in the problem
- the *highest complex cognitive process* that is necessary to solve it (for both information and mental procedures)
- the *number of intermediate complex cognitive processes* required to solve it (with respect to information and mental procedures).

Example Problem: Rank each case from the highest to the lowest acceleration based on the drawings shown in the figure below. Assume all accelerations are constant and use the coordinate system specified in the drawing. Note: zero is greater than negative acceleration, and ties are possible. [22]



A student required to solve this problem should know the concepts of velocity and acceleration. Therefore we conclude that the problem involves declarative knowledge. Also, the student should know the algorithms of interpreting the diagrams. Hence the problem involves procedural knowledge as well. These two types of knowledge are processed in different ways during the problem solving protocol. Concerning declarative knowledge, the student has to:

- *recall* the concepts of velocity and acceleration;
- decide what are the key elements that need to be taken into account (*integrate* the facts);
- represent the information (*symbolize* the facts);
- *rank* the time sequences.

Regarding procedural knowledge the student needs to *execute* the algorithm of extracting the information from diagrams.

In conclusion, here is how this problem would be classified according to TIPP (refer to Fig. 2):

- *type of knowledge* – the problem involves both declarative and procedural knowledge;
- *number of cognitive processes involved*
  - for information: retrieval, comprehension and analysis;
  - for mental procedures: retrieval;
- *highest cognitive process involved*
  - for information: analysis;
  - for mental procedures: retrieval.

How do we build different classes of physics problems?

Depending on the purpose of the problem classification, meaningful groups of physics problems with similar parameters can be defined. For instructional needs, we find that a classification taking into account the type of knowledge and the highest complex cognitive process required to solve the problem is often enough. However, for research and assessment purposes, a finer-grained characterization of physics problems is needed, which also includes the component cognitive processes and the type of declarative or procedural knowledge (refer to Fig. 2).

TESTING

The validity of our taxonomy will be established in the few ways [23]. First, Marzano's taxonomy will be confronted with the existing cognitive science and expert-novice research concerning physics problem solving. This will be done in order to ensure well-documented and complete descriptions of the cognitive processes that take place during physics problem solving. Second, we will evaluate the extent to which the taxonomy is in agreement with modern models of students thinking. In this way we seek to adapt Marzano's taxonomy to physics problem solving. Third, we will check if certain cognitive processes assigned to a problem (using TIPP) are in fact used by students when they solve it. To do this, we will use 5 PER articles that publish extensive interviews with students solving physics problems.

To assess the reliability of our classification scheme, we are selecting from [11-16, 24] a set of about 100 text-based and PER-based physics problems with a high degree of diversity. These problems will first be categorized in terms of TIPP parameters by the proposal team, and then they will be presented to others who will make an independent categorization. The results for the assigned parameters will be compared to the proposal team results. As a statistical measure, Cohen's kappa coefficient [25] will be calculated in order to determine the degree of inter-rater reliability. Moreover, the process will be

repeated at a later time to verify that the results do not vary over time (stability reliability or "test-retest" reliability).

CONCLUSIONS

We are developing a taxonomy for introductory physics problems that can be used for designing curricular materials with a cognitive component and for modeling the physics problem solving process. While doing so, we analyze existing collections of physics problems and aim to identify the cognitive process needed to solve them. After an extensive review of text-books we find that, for the knowledge domain of information, most standard text-book problems engage cognitive processes up to analysis, while PER-based problems reach the cognitive level of knowledge utilization. With respect to mental procedures, we find that text-books contain very few problems that require cognitive processes higher than retrieval, while some PER-based problems go up to analysis.

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