# Developing Thinking & Problem Solving Skills in Introductory Mechanics

Vincent P. Coletta and Jeffrey A. Phillips

Department of Physics, Loyola Marymount University, Los Angeles, CA 90045 USA

**Abstract.** We report on the Thinking in Physics (TIP) project, which helps students develop basic skills necessary for learning physics. We describe methods used to improve students' thinking and problem-solving skills in TIP introductory mechanics classes, and the effect these methods have had on student learning. The project is supported by NSF grant 0633353.

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#### INTRODUCTION

Interactive methods of teaching physics are more effective than traditional methods [1,2]. However, our research demonstrates that those students who have weak reasoning skills are likely to have limited success in physics even in interactive courses [3,4,5]. The Lawson Classroom Test of Scientific Reasoning Ability is a multiple-choice test that includes questions on conservation, proportional thinking, identification and control of variables, probabilistic thinking, and hypothetico-deductive reasoning [3,6]. We have found a strong correlation between individual students' normalized gains on the Force Concept Inventory (FCI) and their preinstruction scores on the Lawson Test in IE introductory mechanics classes at Loyola Marymount University (LMU) (N = 98, r = 0.54) and at Edward Little High School (ELHS) (N = 199, r = We have also found strong, positive correlations between individual students' instruction SAT scores and their normalized FCI gains at ELHS (N= 335, r = 0.57) and at LMU (N = 292, r =0.46).

Our research reveals that many students come to IE physics classes unable to use certain scientific reasoning skills needed to learn physics, and for those students, achieving good conceptual understanding in mechanics is unlikely. We created the Thinking in Physics (TIP) program to enhance those reasoning skills. TIP identifies students as being at risk in introductory physics, based on their pre-instruction performance on the Lawson test and the SAT. We have previously described some of our methods and

the effect they have had on students' understanding of mechanics concepts, as measured by improved normalized gains on the FCI [7]. Here we focus on our efforts to improve both students' scientific reasoning skills and their problem solving abilities.

## DEVELOPING SCIENTIFIC REASONING

Understanding variables and their relationships is of great importance in science, and many students have difficulty in this area. The ten questions on the Lawson test that deal with identification and control of variables and proportional variables are the questions that show the greatest correlation with FCI normalized gains. Various TIP activities are designed to develop understanding of the meaning of a variable, how variables can be related and controlled, kinds of relationships between variables, such as proportionality, constant sum, and constant difference, and algebraic and graphical representations of variable relationships.

Many of the activities developed in the Cognitive Acceleration through Science Education (CASE) [8] and Numerical Relationships (NR) [9,10] programs were useful guides for us in developing TIP activities. These activities often involve student group work, guided by worksheets, and include lab experiments. TIP often uses the context of physics to teach thinking about variables.

When we give TIP students preinstruction tests in which *all* questions require the use of proportional reasoning, most students score close to 100%. And yet many of these same students miss the proportional reasoning questions on the Lawson test. These

students know how to apply proportional reasoning, but often do not know *when* to apply it. Therefore our TIP proportional reasoning exercises explore different kinds of relationships between variables and emphasize recognizing when a relationship between two variables is proportional.

In a TIP experiment related to Newton's second law, one student pulls a cart on which a second student is seated, while maintaining a constant force. The cart is a sheet of plywood with four low friction, Rollerblade wheels. The cart is pulled with a rope and spring scale, so that the student who is pulling can monitor the force during the motion. Students are often surprised to find that they are initially not able to maintain a constant tension of 20 N (which is significantly greater than the friction force), because they do not realize that they must accelerate to do so. The riding student uses a metronome and marks the floor at one-second intervals, so that the distance traveled as a function of time can be measured. This experiment serves both to develop students' understanding of Newton's second law, but also to develop their facility with handling multiple variables and their relationships.

When beginning the study of conservation laws, students are asked to propose expressions for momentum that would lead to a constant sum relationship. The instructor facilitates a discussion and the class arrives at several quantities. Typically, they propose speed, speed times mass, velocity, and velocity times mass as the conserved quantities. To test their models, students use two low-friction cars on a one-dimensional track with two motion sensors. Using different ends of the cars, perfectly inelastic and (approximately) elastic collisions are performed. Students identify four to six unique kinds of collisions and then form a matrix of experiments and models. For each combination students are asked to state what the experimental outcome would be if that momentum model were correct. Typically, students require assistance from the instructor or teaching assistant to complete this step. By the end of the lab period, the students will have identified the correct physical model and gained experience in working with a new kind of variable relationship as well as formulating and testing hypotheses.

By the end of the semester, when students are studying fluids, they are more comfortable identifying relevant variables and discovering relationships with minimal instruction. One lab includes multiple stations where students observe various static and dynamic fluid phenomena. One station includes a half-filled fish tank, a small acrylic box with a length scale engraved on the side and several 50 g masses. The acrylic box serves as a boat in which the masses can be placed. Students are simply asked to identify

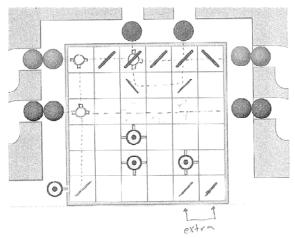
pertinent variables and their relationship. From their observations, they are then asked to determine how the pressure depends on the depth under water. In all activities, the kind of variable relationship is highlighted along with the physics concepts.

## DEVELOPING PROBLEM SOLVING SKILLS

Methods of developing physics problem solving skills have been emphasized by many [11,12,13,14]. TIP develops students' problem solving skills by developing general thinking skills, by providing a solid physics conceptual base, by modeling effective problem solving strategies, and by encouraging metacognition regarding problem solving. encourages students to use the four step method of problem solving first proposed by Polya [15]: i) formulate the question; ii) plan a solution; iii) execute the plan; iv) review the solution. The specific implementation of each step depends on the problem. The general approach is emphasized in different contexts, including everyday problem solving, puzzles, and physics problems. Application to everyday problems and puzzles helps students appreciate that planning should engage their full creativity.

Developing successful problem solving strategies in a computerized game setting can be helpful for understanding successful strategic thinking in physics and is attractive for students. Using software developed by the MIND Research Institute, TIP computer games build skills, using visual techniques that do not rely on language abilities, but which do make heavy demands on working memory, requiring planning steps in advance to achieve a favorable outcome. Games steadily increase in difficulty, with the most difficult games being quite challenging.

The lack of instructions for the MIND games forces students to perform step 1 of Polya's method. Games are untimed to encourage students to carefully plan their solutions and review any failed attempts. We encourage students to apply the same kind of resourcefulness and perseverance to physics problem solving that they do in everyday problem solving and in games. In classroom discussions and written assignments, we ask students to reflect on their methodology in all games and puzzles and identify the components that would transfer to physics problem solving.



**FIGURE. 1** A student solution to a MIND game. A laser beam is to be emitted from a laser gun in the lower left corner. The beam changes direction if it hits one of the reflectors, and, if the beam hits other laser guns, causes them to emit more laser beams. A player moves the reflectors and laser guns over the grid so that the laser beams will knock all of the balls out of the path and enable a penguin to travel through the passage. A student has indicated a good solution on this copy of the computer screen.

TIP addresses many facets of student performance. One of the common problems is impulsiveness and lack of attention to detail. Feuerstein's dot exercises [7,16] are used to address this at a fairly low level, and Sudokus and other similar math puzzles are used to address this at a more advanced level. Both instill in the students an appreciation of the need to restrain impulsiveness, to be attentive to detail and to make changes when mistakes are made. Such planning, monitoring and adjusting comprises key selfregulation skills in problem solving. After completing puzzles, students reflect on the process by which they arrived at their solutions and compare methodologies with their classmates. These discussions allow the instructor an opportunity to reference Polya's steps, especially planning and reviewing, as well as show parallels with physics problem solving. Students are able to build confidence in their self-regulation skills in these puzzle contexts.

Students are asked to reflect on their thinking throughout the semester. They are asked to keep a written journal that is shared with the instructor, who provides feedback and grades them, based solely on completing the assignment. Writing prompts range from conceptual physics questions to ones that require students to engage in metacognitive thought. Throughout the semester, students are asked to periodically reflect on how their thinking is changing.

#### **RESULTS**

### **Scientific Reasoning**

TIP was integrated into one section of introductory mechanics taught by one of us in the Fall of 2007 and into three sections of introductory mechanics in the Fall of 2009, two sections taught by one of us and the third taught by the other. In the Fall of 2008 one of us taught a pre-physics Thinking in Science course, designed to prepare at risk students for introductory mechanics, using TIP methods. All four introductory mechanics sections were similar both in size (24 to 28 students each) and in class average preinstruction scores on the Lawson Test (68% to 73%) and on the SAT (1137 to 1161). The Thinking in Science class was smaller (13 students) and, with exclusively at-risk students had lower average Lawson and SAT scores, 62% and 1057 respectively. The Lawson Test was administered in all five of these TIP classes, both pre and post instruction. Lawson Test scores, averaged over all five TIP classes, improved from 69% preinstruction to 78% postinstruction, corresponds to an average normalized Lawson gain of 0.29. The average normalized gains of the five classes varied significantly (0.40, 0.38, 0.26, 0.20, and 0.15), and individual students' normalized gains varied widely: standard deviations of Lawson gains in the five sections ranged between 0.3 and 0.5.

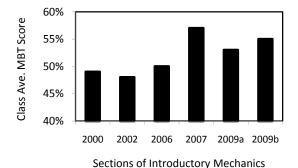
#### **Problem Solving**

The Mechanics Baseline Test (MBT) is a standardized exam sometimes used as a measure of problem solving ability. One of us has administered the MBT, postinstruction, in six of his IE introductory mechanics sections from Fall 2000 to Fall 2009. The first three sections ('00, '02, and '06) were before the TIP program began, and the last three ('07, '09a, and '09b) were TIP classes. Because the instructor was the same and the classes were similar in composition, the MBT scores in these classes provides a measure of the impact that TIP has had on students' problem solving ability. The TIP and non-TIP sections were similar in size (24 to 32 students) and in class average preinstruction scores on the FCI (26% to 31%) and on the SAT (1092 to 1164). The Lawson Test was not given in the pre-TIP classes.

The general structure of all six of these IE intro mechanics classes was the same: one 2-hour weekly lab and two 75-minute weekly classes – one class devoted to developing conceptual understanding without detailed problem solving, utilizing many concept-based clicker questions and group discussion (similar to Peer Instruction), and one class devoted to

problem solving, in which students worked in groups of two to four on previously assigned homework problems, with the instructor guiding the work. The problems included fairly typical textbook problems, as well as estimation problems and extended context problems. Most problems were from the text *Physics Fundamentals* [17]. Fifteen-minute quizzes were given at the end of each problem session. The importance of both conceptual understanding and problem solving was emphasized; tests consisted of 50% concept questions and 50% problems.

In addition to the TIP methods described above and common to all TIP classes taught by either of us, the three TIP sections taught in Fall '07 and Fall '09 had an added feature: special tutorial sessions for at-risk students. In the Fall '07 class, 12 of the 24 students were identified as at-risk, based on their preinstruction Lawson scores of 75% or less and were invited to meet outside of class to engage in further TIP activities. All but one of these students agreed to the additional time. The meetings were arranged to accommodate student schedules and resulted in groups of two to four students at each meeting time. The time devoted by students in these meetings ranged from 1.5 to 3 hours per week. These tutorials sections were guided by the instructor. In the two Fall '09 sections, at-risk students were identified on the basis of their Lawson &/or SAT scores and were invited to participate in tutorial meetings in groups of 3 or 4 students. Of the 51 students enrolled in the two sections, 22 students participated in the tutorials, meeting weekly for 1.5 hours in sessions guided by one of the course's two undergraduate TAs. MBT scores indicate that TIP students demonstrated stronger problem solving skills than students in the earlier classes.



**FIGURE 2:** Class average scores on the MBT in pre-TIP classes before 2007 and in TIP classes in 2007 and 2009. Standard errors in the class average scores ranged between 2% and 4%. The Fall '07 class average,  $57\% \pm 3\%$  (se) was more than two standard errors above the class averages in any of the pre-TIP sections.

#### **SUMMARY**

We developed the Thinking in Physics program, consisting of an array of activities designed to help students whose pre-instruction scores on the Lawson test and/or the SAT indicate that they are unlikely to achieve substantial learning in IE mechanics without special help. Student participants have demonstrated post instruction improvement on the Lawson test and significantly stronger problem solving skills than in preTIP IE classes. We are continuing to fine-tune the TIP program and to collect data.

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