Addressing Barriers to Conceptual Understanding in IE Physics Classes

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 project, which helps students who demonstrate weak scientific reasoning skills, as measured by low preinstruction scores on the Lawson Test of Scientific Reasoning Ability. Without special help, such students are unlikely to achieve a good conceptual understanding of introductory mechanics. The project is supported by NSF grant 0633353.

INTRODUCTION

Physics Education Research has established the superiority of interactive teaching methods over traditional methods of teaching physics [1,2]. However, our research demonstrates that those students who demonstrate weak scientific reasoning skills are likely to have limited success in physics even in interactive courses [3,4]. Our Thinking in Physics program identifies students as being at risk in introductory physics, based on their pre-instruction performance on tests of reasoning, such as the Lawson Classroom Test of Scientific Reasoning Ability [3,5]. The instructional program we provide these students includes adaptations of methods used in other programs designed to enhance reasoning ability.

The Force Concept Inventory (FCI) [6,7] is widely used as a measure of students' understanding of basic concepts in Newtonian mechanics. When the test is given both at the beginning and end of an introductory mechanics course, a student's pre- and post-instruction scores can be used as a measure of conceptual learning achieved during the course. In order to compare the learning achieved for students with quite different pre-instruction scores, a useful measure is the normalized gain G:

$$G = \frac{postscore\% - prescore\%}{100 - prescore\%}$$

Research demonstrates that Interactive Engagement (IE) methods are consistently more effective than traditional methods [1,2]. Traditional courses consistently result in class average G's of only about 0.2, whereas IE classes produce consistently higher G's, typically in the range $0.3 - 0.6$.

The Lawson Test is a multiple-choice test that includes questions on conservation, proportional thinking, identification and control of variables (Fig. 1), probabilistic thinking, and hypothetico-deductive reasoning.
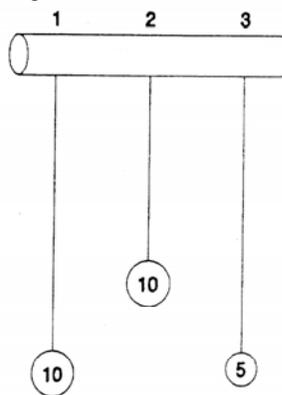
FIGURE 1. An edited version of Lawson questions involving control of variables: Three strings have either 5 or 10 unit weights attached to their ends Suppose you want to find out whether the length of a string has an effect on the time it takes to swing back and forth. Which strings would you use to find out? a) only one string; b) all 3; c) 2 & 3; d) 1 & 3; e) 1 & 2. Because a) you must use the longest strings; b) you must compare strings with both light and heavy weights; c) only the lengths differ; d) to make all possible comparisons.

We have found a strong correlation between students' conceptual learning in IE physics classes, as measured by FCI G, and their preinstruction reasoning skills, as measured by Lawson's Test [3,4]. When individual student FCI G data are grouped into quartiles corresponding to Lawson preinstruction scores, the variation of G with Lawson score is dramatic, as seen in Fig. 2, which contains data for IE

classes at Loyola Marymount University (LMU), Edward Little High School (ELHS), and the University of Colorado (CU) [8]. The correlation between Lawson score and FCI *G* has been replicated by others [9,10].
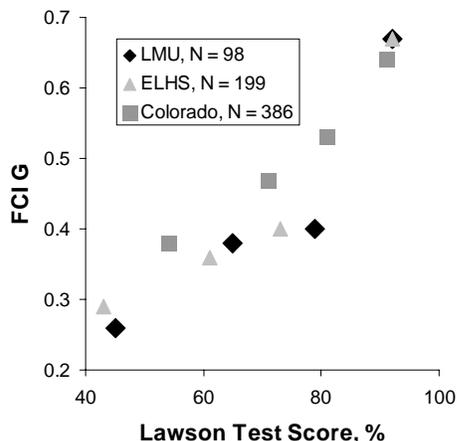
FIGURE 2. Correlation between Lawson preinstruction scores and normalized FCI gain, with data grouped into quartiles for each school. The correlation coefficients for individual student data are 0.54, 0.53, and 0.42 for LMU, ELHS, and CU respectively.

We have also examined pre-instruction SAT scores and normalized FCI gains for individual students in IE courses in introductory mechanics at ELHS in Maine (N= 335) and at LMU (N = 292), and found strong, positive correlations for both populations ($r = 0.57$ and $r = 0.46$ respectively) [11].

THINKING IN PHYSICS

Our research reveals that many students come to IE physics classes not manifesting 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 program to enhance those reasoning skills, building on past worldwide efforts to improve reasoning among various populations.

Philip Adey designed his Cognitive Acceleration through Science Education (CASE) program [12] for middle school children. One-hour lessons were inserted into the regular science curriculum once every two weeks for two years. These lessons all involve some kind of science content, but their purpose is to teach scientific reasoning skills: identification and control of variables, proportional reasoning, probability and correlation, and use of abstract models. On average, students who participated in CASE at dozens of schools throughout the UK averaged one full grade higher in science, mathematics, and even

English than did students in control groups. CASE methods have been successfully replicated throughout the world.

Israeli psychologist Reuven Feuerstein, who, like Philip Adey, was inspired by Piaget and Vygotsky, developed the Instrumental Enrichment (FIE) program to improve the intellectual level of children with very low IQs [13]. FIE is now in use in over 75 countries and has versions that are appropriate to different ages and cognitive levels. FIE consists of 14 paper-and-pencil tasks that, unlike CASE, are designed to be content free. One of the most effective involves connecting sets of dots to form simple geometric shapes. Students are shown a picture with a few simple shapes, for example a square and two triangles, along with what appears at first to be a random array of dots (Fig. 3). When the dots are connected by the proper lines, they reproduce the simple geometric shapes, a square and two triangles in our example. However, the shapes have been rotated and overlap, making the identification of shapes more difficult. There are many such sets of pictures of gradually increasing complexity. Initially the children have great difficulty, because they tend to impulsively connect dots, which give rough approximations to the desired shape, but are incorrect. Gradually they learn to restrain their impulsiveness, to pay attention to detail, and to develop strategies (such as find the square first), all of which are useful problem solving strategies in any context.
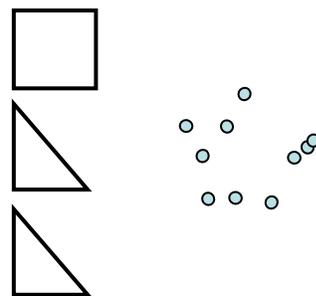
FIGURE 3. An example of a Feuerstein style dot exercise. When the dots are connected by the proper straight lines, the shapes on the left are reproduced, though rotated.

Kurtz and Karplus developed the Numerical Relationships (NR) activities to help middle school students with proportional reasoning, specifically distinguishing between constant ratio, constant difference, and constant sum relationships [14,15]. Instruction was provided during fifteen class hours over three weeks and was based on the Learning Cycle pioneered by Karplus [16]. Students who used the NR materials showed great improvement, whereas those enrolled in control sections did not.

The Thinking in Physics program addresses many facets of student performance. One of the common problems is impulsiveness and lack of attention to detail. Feuerstein's dot exercises are used to address this at a fairly low level, and Sudoku puzzles are used to address this problem at a more advanced level. The students must develop their own strategies for both exercises; no strategies are provided to them. Students progress quickly through the dot exercises, but the development of effective strategies for solving Sudokus takes time, and after a brief introduction, we ask students to work independently on Sudokus, using a website (www.sudoweb.com), so that little instructional time is used. Most students like both of these activities, and show dramatic progress on them. Both instill in the students an appreciation of the need to restrain impulsiveness, to be attentive to detail, and to think strategically. We encourage metacognition and self-regulated thinking through class discussions in which students analyze their thinking about solutions. Without such habits, students often use the first idea that occurs to them, whether or not it is appropriate [17,18].

A proper understanding of 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, and kinds of relationships between variables, such as proportional relationships. We also consider algebraic and graphical representations of relationships between variables. Many of the CASE and NR activities were useful guides for us in developing these activities. TIP activities often involve student group work, guided by worksheets, including lab experiments. TIP often uses the context of physics to teach thinking about variables. Examples of TIP control of variables activities follow.

I Chimes Students are supplied with 20 tubes made of various metals. The tubes vary in length and in inner and outer diameters, and are suspended from strings. Students are asked to identify the variables that describe the tubes. After stiking various tubes and noting that they produce sounds of varying pitch, they are asked how they would design an experiment to identify variables that affect pitch. In this exercise students are not asked to perform the experiment. Instead the emphasis is on identification and control of variables in planning an experiment.

II Rolling Students are given a dozen round, symmetric objects of varying mass, radius, and shape (billiard balls, aluminum cylinders, hollow tubes, golf balls, etc.) and an inclined plane. Students are asked to first identify the variables that describe the objects, to predict which of those variables will affect the time it takes to roll from the top to the bottom of the incline, starting from rest, and to predict which of the objects will reach the bottom in the least time. Students then plan an experiment to test their predictions, and finally perform the experiment. Although some groups begin with random trials to verify their prediction of the fastest object, all eventually realize that they must control variables and design a systematic series of measurements.

TIP develops students' problem solving skills by modeling effective problem solving strategies. TIP encourages students to use the four step method of problem solving proposed by Polya [19]: 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. 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. We encourage students to apply the same kind of resourcefulness to physics problem solving that they do in everyday problem solving and in games.
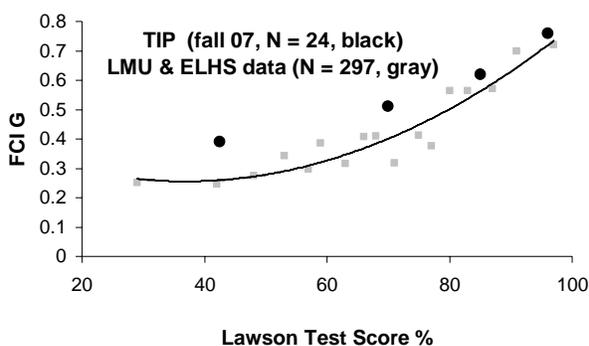
RESULTS

In spring 2006 and spring 2007, we began pilot versions of TIP to determine the effectiveness of our initial materials, with two students in the first pilot and three in the second. These students were identified as at-risk, based on their Lawson scores. The students volunteered to meet 2 hours per week outside of their regular IE introductory mechanics class. For the five students who participated in either of these first offerings, the mean normalized FCI gain was 0.59 ± 0.12 (s.e.), 2.8 standard errors above the FCI G of 0.26 predicted on the basis of their mean Lawson score of 45%.

TIP was integrated into an introductory mechanics course taught by one of us in the fall of 2007. The 24 students in the course had pre-instruction Lawson scores ranging from 13% to 100%. Three hours of class time was devoted to TIP activities, and two of

twelve lab periods were devoted to assessment and to special TIP labs. Twelve 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. The mean FCI normalized gain for these eleven students was significantly higher than would have been predicted on the basis of their Lawson scores in an IE class: their average G was 0.47 ± 0.06 (s.e.), 2.5 standard errors above the mean G of 0.30 predicted for these students on the basis of their mean Lawson test score of 57%. The nonparticipating at risk student had a Lawson score of 50% and FCI G of 0.26. Fig. 4 shows the class results divided into Lawson quartiles, along with binned reference data from earlier IE classes at LMU and ELHS and a best fit curve [11]. The Lawson Test was also administered at the end of the course, and the average normalized Lawson gain for the at-risk students was 0.16 ± 0.11 (s.e.).

In the fall of 2008, a new 3-unit elective course, Thinking in Science, was taught by one of us. The entire course was devoted to TIP activities. Students could enroll only with the instructor's permission, which was based on low SAT scores. Most of the 13 students in this class showed a significant improvement in scientific reasoning skills: the class average normalized Lawson gain was 0.38 ± 0.08 (s.e.). Most of these students have not yet taken physics.

FIGURE 4. TIP results compared with results of previous IE classes (the same LMU & ELHS data as in Fig. 2, but with the combined data divided into 17 bins [11]). Although several hours of class time were devoted to TIP activities for all 24 TIP students, 11 of the 12 students with the lowest Lawson scores participated in additional weekly meetings.

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 indicate that they are unlikely to achieve substantial conceptual learning in IE mechanics without special help. Student participants have demonstrated post-instruction improvement on the Lawson test and significantly higher normalized FCI gains than would have been predicted on the basis of pre-instruction Lawson scores. We are continuing to fine tune the TIP program and to collect data.

REFERENCES

1. R. R. Hake, *Am. J. Phys.*, **66**(1), p. 64-74 (1998).
2. E. F. Redish and R.N. Steinberg, *Phys. Today*, **52**(1): p. 24-30 (1999).
3. V. P. Coletta and J. A. Phillips, *Am. J. Phys.*, **73**: p. 1172-1182 (2005).
4. V. P. Coletta, J. A. Phillips and J. J. Steinert, *Phys. Teach.*, **45**: p. 626-629 (2006).
5. A. E. Lawson, *Am. Biol. Teach.*, **62**(7): p. 482-495 (2000).
6. D. Hestenes, M. Wells, and G. Swackhamer. *Phys. Teach.*, **30**(3): p. 141-58 (1992).
7. E. Mazur, *Peer instruction: a user's manual*, Upper Saddle River, N.J.: Prentice Hall (1997).
8. M. A. Dubson and S. J. Pollock. AAPT *Announcer* **36** (2): 90 (2006).
9. K. Diff and N. Tache, *AIP Conf Proc.* **951**: p. 85-87 (2007).
10. P. Pamela and J. Saul, AAPT Announcer **36**: p. 89 (2006).
11. V. P. Coletta, J. A. Phillips and J. J. Steinert, *Phys. Rev. ST: Phys. Educ.*. *3* p. 010106-1 – 010106-5 (2007)
12. P. S. Adey and M. Shayer. *Really Raising Standards: cognitive intervention and academic achievement*. London: Routledge (1994).
13. R. Feuerstein, *et al.*, *Instrumental enrichment: An intervention program for cognitive modifiability.* Baltimore: University Park Press. (1980).
14. B. Kurtz, dissertation, University of California (1976).
15. B. Kurtz and R. Karplus, *Sch. Sci. Math.*, **79**(5): p. 387-398 (1979).
16. J. M. Atkin and R. Karplus, *Sci. Teach.*, **29**(5): p. 45-51(1962).
17. J. P. Mestre et al, *J. Res. Sci. Teach.*, **30**(3): p. 303-317(1993).
18. J. H. Larkin et al, *Science,* **208**: p. 1335-1342 (1980).
19. G. Polya, *How to Solve it.* Princeton, NJ: Princeton U. Press (1945).