SPIRALPhysics Active Learning

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Editors Note: Please see the note on page 11.

A series of workbooks, *SPIRALPhysics*, have been developed and used in place of a standard textbook in the introductory physics course sequence at Monroe Community College for several years. These workbooks, designed for use in an active learning environment, arrange topics such that students receive repeated exposure to concepts over an extended time interval, each time with an incremental increase in complexity. These workbooks emphasize multiple-representation problem solving techniques and goal-less problem statements. We will discuss the structure of and the rationale behind the *SPIRALPhysics* workbooks as well as the results of several assessments.

I. Introduction

Research in physics education reveals serious weaknesses in conventional instruction for students in introductory college physics courses. Students who perform satisfactorily on tests are nonetheless found to have little gain in qualitative understanding,[1] disorganized knowledge hierarchies,[2] and primitive problem solving skills.[3] Furthermore, many students enter physics courses with strongly held beliefs on the way the physical world behaves, which at best are only partially consistent with the proper perception, and leave with the majority of these views intact.[4]

In response to these findings,[5] *SPIRALPhysics*, a series of active-learning workbooks which incorporate some of the results of physics education research into an introductory classroom curriculum, were developed. In *SPIRALPhysics*, activities are sequenced to help students construct a knowledge hierarchy on a foundation of qualitative, conceptual understanding of physics. This is accomplished through repeated exposure to concepts over an extended time interval, each time with an incremental increase in complexity. This meticulous construction, by the student of a knowledge hierarchy allows rather rapid assimilation of new concepts as the course progresses. This foundation of conceptual knowledge, in conjunction with explicitly structured problem-solving techniques, such as multiple-representation problem solving, encourages student development of more mature and expert-like problem-solving skills.

SPIRALPhysics was developed for use in the introductory physics courses at Monroe Community College (MCC), which typically serve between 40 and 50 students per section. So as not to adversely effect transferability, implementation of the workbooks require only minimal reduction in content coverage compared to traditional instruction at MCC.

II. Features of SPIRALPhysics

A course taught using a *SPIRALPhysics* workbook differs from a conventionally taught physics course in five distinct ways. These are the use of an active learning environment, the emphasis on multiple-representation problem solving techniques, the arrangement of topics such that students receive exposure to the same material numerous times, the restriction of students to a small set of fundamental equations to use in solving problems, and the use of goal-less problem statements.

A. Active learning environment

First, the SPIRAL classroom is an active one, with a minimal amount of instructor time spent lecturing or doing example problems. Instead, student groups work on activities in the workbook which have been designed and arranged to lead students to construct the concepts and ideas normally relayed through lecture. To encourage active group engagement, these tasks: (1) are sufficiently challenging so that even the better students can benefit from peer instruction, (2) do not simply involve the application of a numerical algorithm, and (3) are either open-ended, ambiguous or conceptual in nature so that verbal reasoning skills are required to achieve a solution. Typical end-of-the-chapter exercises are not effective active-learning tasks.

To implement active learning into the classroom, students are assigned into groups of four. These assignments mix students of different abilities, and the groups are changed every three weeks. Groups work on tasks from the workbook, which serves as the only text for the course. Workbook activities typically have both a qualitative and quantitative portion. The qualitative portions are typically worked on and discussed during class time, while the quantitative portions are assigned to different groups to be completed outside of class time. Groups are assigned the task of either producing a written solution or an oral presentation on the completed quantitative activity.

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About 75% of the activities are assigned for written solutions, with the remainder presented orally. The written solutions are graded and then uncorrected copies are made available to the class. There are no corrected solutions to problems available to students. Students are encouraged to examine other groups work critically and to discuss with other groups any questions they may have on their solutions. The oral presentations are graded by both the other students and the instructor. In addition to the group tasks, there are numerous unannounced quizzes. Sometimes the students will be allowed to work in their groups, while at other times they will be graded individually. These quizzes are typically not detailed numerical solutions to problems but rather qualitative or conceptual questions. The students are tested individually.

B. Multiple-representation problems
Second, students are required to utilize the technique of multiple representation problem solving when attempting to analyze a physical scenario. Multiple representation problem solving requires students to construct multiple representations of a physical situation, for example pictorial, qualitative and graphical representations of the same situation, before constructing a mathematical representation (i.e., applying formula). This can lead to an increased understanding of the underlying physics of the situation as well as a keener insight into the proper problem solution path to take. Students are explicitly taught how to construct these different representations. Then, students complete workbook activities which were designed to facilitate moving between representations.

For example, students are always required to construct position, velocity and acceleration versus time graphs for any kinematics situation before exploring the situation mathematically. Furthermore, questions are posed to the students concerning their understanding of the graphical representations. The problems in this section are entitled Translating Physics to convey to the students that solving a physics problem is really a matter of translating a verbal description of a situation into, ultimately, a mathematical description. A situation is described, and the students are instructed to sequentially construct a motion diagram of the situation, a graphical representation of the situation, and finally a tabulation of what is known and unknown about the situation. The students are also required to explicitly describe the event at which the information is tabulated. This explicit description aids the students in structuring their understanding of the situation. Only after constructing these multiple representations of the same physical situation do the students apply the equations of kinematics.

C. Spiral format of topics
Third, the sequence of topics covered in the workbooks is formatted in such a way that students get repeated, or spiral, exposure to the same concepts throughout the course. The workbook is designed such that about five weeks of class time is devoted to each of the three cycles, or spirals, through the material.

On the first pass through particle mechanics, students are presented with nominally one-dimensional situations in which all forces are constant. The requirement that students simultaneously grasp the concepts of Newtonian mechanics, become comfortable with vector notation, understand vector algebra, and use calculus in a meaningful way has historically led to a very large attrition within the first few weeks of MCCs calculus-based physics I course. A large portion of this attrition can be avoided by simply not overwhelming the students at the start. For the first five weeks of the course, the workbook concentrates on the physics, without unnecessary mathematical complexity. The physics concepts alone are complex enough.

The restriction to one dimension and constant forces allows the introduction of the work-energy and impulse-momentum relations much earlier in the semester than does the traditional sequence of topics. This is advantageous because on subsequent assignments students are not instructed on what approach, either the utilization of Newton's laws, work-energy or impulse-momentum, to take in solving a particular problem. Instead, students must analyze the information presented in the problem statement, and the information they desire to obtain, and then decide which approach will allow them to obtain that information as efficiently as possible. By not explicitly instructing the student which problem solution approach to take, students are forced into using more mature and expert-like problem-solving skills. In addition, the introduction of the work-energy and impulse-momentum relations early in the semester, with repeated exposure throughout the semester, aids the students in understanding the complementarity of these different analysis techniques.

On the second pass through the material, the vector notation and vector algebra framework that is useful in solving multi-dimensional problems is introduced. The use of vector notation as a means of simplifying the expression and solution of certain

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problems is encouraged. In addition, the level of difficulty of the problems in this second cycle increases, although the students are still exposed to scenarios involving only constant forces.

By the third pass through particle mechanics, all of the students have been exposed to at least ten weeks of a college-level calculus course. The concepts and equations of particle mechanics are re-examined in scenarios involving non-constant forces. Also, on this spiral through the material the level of mathematical abstraction is significantly higher than before, and many fairly sophisticated physics problems involving calculus are assigned and successfully completed.

D. Restricted equation set

The fourth distinction between a course structured around the SPIRAL workbooks and a more traditionally taught physics course is that the SPIRAL workbooks restrict students to a much smaller set of equations to use in solving problems. The workbooks are designed assuming the instructor will not discuss, derive or allow students to use any special-case formula.[7]

The rationale is twofold. First, experience shows that students quite often forget the restrictions to the use of special-case formula, and thus use them to analyze inappropriate scenarios. For example, students often use the range formula[8] from projectile motion for a projectile launched over unlevel ground.

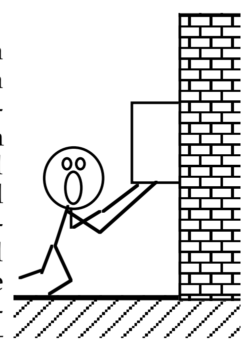
Second, the plethora of equations presented in introductory textbooks serves to reinforce the typical students misconception that physics is merely a collection of formula, and that solving problems is simply reducible to finding the correct one. There are 27 numbered formulas in the chapter on one-dimensional kinematics in a popular introductory physics text.[9] Obviously, instructors know which of these relations are important, but many students do not. There are only two independent equations in the study of kinematics: the definition of velocity and the definition of acceleration. Therefore, the SPIRAL workbooks refer to and students are restricted to using only two relationships to solve kinematics problems. The misconception that solving physics problems is reducible to finding a magic formula prevents students from developing mature problem-solving skills. In order to avoid this scenario, students are required to start every solution from a very small set of general relationships.

E. Goal-less problem statements

A final distinction between pedagogies is the near exclusive use of goal-less problem statements in the *SPIRALPhysics* workbooks. Goal-less problem statements do not contain an explicit target variable for which to solve. The explicit appearance of a target variable can encourage student use of a means-ends heuristic to solve the problem the student searches for any equation which contains the target variable and attempts to plug the numerical values given in the problem statement into this equation.

Although this approach can be used successfully to calculate the numerical value of the target variable, it discourages the development of a qualitative understanding of the phenomenon under investigation and encourages the misconception that physics is, indeed, merely a collection of formula. Goal-less problem statements require students to break away, to some degree, from a simple means-ends approach to problem solving and hopefully encourage a more expert-like attempt at problem solution.

A goal-less problem can simply be a description of a situation in which the students have been instructed to determine everything they can about the physics of the situation. An example is the kinematics situation. After representing the situation pictorially and graphically, and structuring and tabulating the numerical information, the students are instructed to determine as many other kinematic variables as they can. In fact, since the students realize that there are only two independent relationships in kinematics, they can tell at a glance if it is possible to determine all the other kinematic variables or if there is not enough information available to completely specify the situation.



Another example of a goal-less problem is a person applying a specific force at an angle on a block that is placed against a horizontal wall with known coefficients of static and kinetic friction. The ambiguity in the situation forces the student to investigate multiple possible outcomes. Is the block going to move? Will it move up or down? By simply describing a situation, it is left to the student to determine which of the numerous possibilities will result, and then to determine as much about that scenario as possible.

III. Assessment of SPIRALPhysics

Through the use of an active learning environment, the emphasis on multiple representation problem solving techniques, the arrangement of topics such that the student

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repeatedly spirals back over the same material numerous times, the restriction to a small set of fundamental equations for student use, and the use of goal-less problem statements, the *SPIRALPhysics* workbooks attempt to increase student conceptual understanding and problem-solving ability.

In an attempt to assess the impact of the *SPIRALPhysics* workbooks on the introductory physics course, SPIRAL-taught students have been compared to traditionally-taught students on each of five measures. These include the Force Concept Inventory[10] and Mechanics Baseline Test[11] standardized exams, the final grades of students in subsequent physics courses, course completion rate, and student course evaluations. Although much of the impact of the workbooks cannot be measured by such crude, quantitative measures, alternative assessment techniques are rather labor intensive.

A. Force Concept Inventory
A standard measure of student conceptual understanding of Newtonian mechanics is the Force Concept Inventory (FCI), typically administered both pre- and post-instruction. At MCC, students taught with the SPIRAL workbooks have consistently outperformed their peers who were taught in a more traditional manner.

Because of this history of improved conceptual understanding, as well as the results of the other assessment measures, two other members of the MCC physics department elected to teach calculus-based physics I in the fall 1995 semester using the SPIRAL workbook. Both instructors abandoned formal lecture as well as an assigned textbook. Their students also outperformed a traditionally-taught peer group.

B. Mechanics Baseline Test
A valid concern is that the increased gain in conceptual understanding is achieved in the SPIRAL courses at the expense of problem-solving ability. To address this concern, the Mechanics Baseline Test (MBT), which purports to measure problem-solving ability, has been administered to both student populations. At MCC, students taught with the SPIRAL workbooks have consistently outperformed, on this measure of problem-solving ability, their peers who were taught in a more traditional manner.

C. Performance in later physics courses
To address a concern that the use of the SPIRAL workbooks may have an adverse effect on students in subsequent physics courses, the final course grade of previously SPIRAL-taught students has been compared to the final grade of traditionally taught students in MCCs calculus-based physics II course. This course covers rigid body mechanics, waves and thermodynamics.

The SPIRAL workbooks were first used in calculus-based physics I in the fall of 1994. In the following semester, these students joined traditionally taught students in a traditionally taught physics II course. The distribution of final grades of the two groups in physics II was statistically the same.

A *SPIRALPhysics* workbook for calculus-based physics II has been developed. The class composition in physics II is typically a mixture of previously SPIRAL-taught and traditionally-taught students. In a SPIRAL physics II, previous SPIRAL students have consistently outperformed traditionally taught students by a full letter grade. This difference may be due to a familiarity with the style of the SPIRAL workbooks and the active classroom for the previously SPIRAL taught students. However, most students seem to adapt to the course style within the first few weeks. Anecdotal evidence, based on conversations with students, suggests that the deeper and more coherent conceptual understanding of mechanics developed in the previous SPIRAL course has a tangible effect on subsequent comprehension of physics concepts. In addition, it appears that the improved problem-solving skills and strategies developed in SPIRAL physics I are general and transferable.

D. Course completion rate
In addition to deeper conceptual understanding and improved problem-solving ability, the course completion rate of students in the SPIRAL-taught sections is larger than that of the traditionally taught sections. Successful course completion is defined to be a final course grade of C or better.

E. Student course evaluation
Finally, the majority of students seem to enjoy the active classroom approach of *SPIRALPhysics* more than the passive lecture approach of traditional instruction. This conclusion is primarily drawn through conversations with students. However, it is also somewhat apparent in official course evaluations. These evaluations indicate a preference for the SPIRAL approach.

IV. Summary
In summary, it appears that the *SPIRALPhysics* workbooks have been effective at improving student conceptual understanding of mechanics, problem-solving ability and course completion rate.

This has been accomplished primarily through a change in information delivery

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structure and style rather than a change in course content. Although the implementation of an active learning environment requires certain adjustments in course content, these adjustments have been minimal. Given the arrangement of physics topics in the workbooks, at any point during the semester the *SPIRALPhysics* course and the traditional course at MCC are covering different material, although by the end of the semester the material covered is nearly identical.

The improvements in conceptual understanding and problem-solving ability are accomplished through a more effective use of class time and through the careful construction by the student, of a knowledge hierarchy into which the different physical concepts fit logically. This structure, meticulously constructed at the start of each semester, allows rather rapid assimilation of new concepts as the semester progresses.

References

[1] D. Hestenes, M. Wells and G. Swackhammer, "Force Concept Inventory," *The Physics Teacher* 30, 141-158 (1992).

[2] F. Reif and J. I. Heller, "Knowledge Structure and Problem Solving in Physics," *Educ. Psychol*. 17, 102-127 (1982).

[3] A. B. Arons, "Students Patterns of Thinking and Reasoning," *The Physics Teacher* 21, 576-581 (1983); 22, 21-26 (1984); and 22, 88-93 (1984).

[4] I. A. Halloun and D. Hestenes, "The Initial Knowledge State of College Physics Students," *Am. J. Phys*. 53, 1043-1055 (1985); and "Common Sense Concepts About Motion," *Am. J. Phys*. 53, 1056-1065 (1985).

[5] The author was originally exposed to many of the findings of the physics education research community at a Two-Year College Curriculum Development Workshop at Lee College in Baytown, Texas in March 1992, organized by Curtis Hieggelke and Tom O'Kuma. Much of the original work on the *SPIRALPhysics* project was inspired by the workshop leaders, Alan Van Heuvelen and David Maloney, and the workshop participants.

[6] A. Van Heuvelen, "Learning to think like a physicist: A review of research-based instructional strategies," *Am. J. Phys*. 59, 891-897 (1991).

[7] Of course, most equations used in a typical introductory physics course are only valid in special cases. For example, all objects under study must be traveling at speeds much less that that of light. These are global constraints, which effect the validity of the whole equation set available to the student. The restriction to constant forces during the first two spirals through particle mechanics is viewed as a global constraint.

[8] $R = (2v_0 \sin 2ø)/g$

[9] R. Resnick, D. Halliday and K. Krane, *Physics*, Fourth Ed. (Wiley, New York, 1992), pp. 15-25.

[10] D. Hestenes, M. Wells and G. Swackhammer, "Force Concept Inventory," *The Physics Teacher* 30, 141-158 (1992).

[11] D. Hestenes and M. Wells, "Mechanics baseline test," *The Physics Teacher* 30, 159-162 (1992).

Impact of TIPERs

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In spring of 2005 I taught two Physics classes in one of which I implemented ranking tasks from eTIPERs (electrostatics) and mTIPERs (magnetism). This implementation was set up as a test group compared to control (the second class, which was taught without new implementations). I was introduced to these tasks during HTML, Physlets and TIPERs Workshop (Feb. 24-26, 2005).

In the beginning of the semester my students were complaining that the most confusing part of the course was ranking tasks because they were different from the usual textbook physics problems and they took longer to complete the assignment. These tasks required students to engage in a comparison reasoning process that they seldom did. By the end of the semester the number of complaints on this subject has reduced while the number of comments on helpfulness of these assignments grew.

Both classes, the control and the TIPERs test class, received the same final exam that did not contain ranking task-type problems. Students who were assessed using ranking tasks during the entire semester on regular base scored higher on a common final exam than control students, 15% higher overall.

I have observed that although the students had the most difficulty with providing the reasoning for their answer to the problem in the ranking tasks, they have learned how to approach that type of problem logically instead of simply guessing the answer. This training has paid off during the final exam, where the answer may not initially be clear to the student, but they still attempt to approach the problem by reasoning through it and in turn came up with more correct answers than those who were not trained in the same manner.