Physics Illuminations: Supplementing Instruction via Web-Based Self-Study

Ronald L. Greene
Department of Physics
University of New Orleans
New Orleans, LA 70148

work: (504) 280-6714
home: (504) 669-0913
fax: (504) 280-6048

rgreene@uno.edu

Abstract: Gaining conceptual understanding of physics is difficult for many students. Interactive engagement classroom techniques have been shown to help alleviate this problem. This paper describes progress in addressing the problem from a different direction – that of students' out-of-class study. Results from investigations employing several commonly-used assessment instruments indicate that out-of-class study time can indeed be utilized to improve student learning of basic physics concepts.

Keywords: Computer-aided instruction; Self-study; Internet; Java simulations; Web-based

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A National Problem

There has been much research into physics education over the last twenty years, particularly at the introductory college or university level.[1] Many of these studies have shown that incoming students have non-Newtonian preconceptions about motion that are fragmentary, and often internally inconsistent. Yet students hold to them very strongly and resist adopting a Newtonian model of dynamics despite diligent effort on the part of the instructor. Indeed, a traditional lecture approach, which is characterized by passive participation on the part of the students, changes the thinking of remarkably few of them.[2]

For traditionally-taught introductory physics classes average scores on the Force Concept Inventory (FCI) are well below the 60% "*entry threshold* to Newtonian physics" suggested by Hestenes and Halloun[3] as a point where students have "barely begun to use Newtonian concepts." The student-active teaching techniques and greater conceptual emphasis used in interactive engagement classes have been shown to improve student conceptual understanding substantially.[2] However, even for such classes FCI averages are only somewhat above the Newtonian entry threshold. Thus, nationwide, a large majority of students are leaving their introductory physics courses with little understanding of the basic concepts of physics.

What Can Be Done?

In reality, there are limits to what can be done in class to help students learn physics. Doing more requires individualized instruction and productive out-of-class effort on the part of the student. Although time and financial constraints make such instruction by faculty infeasible, individualized computer-aided instruction has had significant positive impact in some areas.[4-5]

With computer-aided instruction users can control many features of their own education process. They can set the pace and the duration of learning. Students who prefer to study alone or students who may be embarrassed to speak out in class are likely to feel more comfortable one-on-one with the computer. On the other hand, students who learn better in a social setting can use the computer in pairs or threes, a learning style that may not be available to them in a traditional physics classroom. All students can benefit from the interactivity and immediacy of a well-designed computer-aided educational system compared to other learning tools, such as textbooks.

The effectiveness of using computers to aid student learning in introductory physics has been discussed by numerous researchers, and remains an active field of study. (See, *e.g.*, Ref. 6-9.) Most early attempts at computer-based instruction in physics produced programs that displayed little or no individualized interaction, or were aimed at teaching problem solving skills. They were also handicapped by our lack of knowledge of how students learn physics. More recently, programs offered under the Physics Academic Software banner and simulation software produced by several of the textbook publishers appear to be very good, although very little of it has been subjected to formal assessment of its effectiveness. Furthermore, the substantial cost of most of this software makes it unrealistic for institutions to obtain sufficient licenses for the typically large numbers of students taking introductory physics at any given time, or for many students to purchase their own copies for home study.

Fortunately, the Internet is proving to be an excellent means for disseminating educational materials. Through it traditional text and still images, as well as audio-visual educational media can be distributed individually and inexpensively. Moreover, tools exist to make these materials highly interactive, a characteristic which research repeatedly shows is essential for student learning. Java applets are among the most powerful of these tools. An Internet search on the keywords “Java” and “physics” will reveal that there are a lot of free physics simulations on the Web. Much of it is very well done from a visual perspective, and can be quite useful to instructors for in-class demonstration where blackboard illustrations fail. However, holding students’ visual attention without engaging their minds does not result in effective learning, and web-accessible software that encourages “minds-on” interaction is still in a minority. Fortunately things are changing, and software tools like Wolfgang Christian’s scriptable Physlets,[10] that encourage instructors to build their own interactive web-based materials, are likely to accelerate this change.

Physics Illuminations

Our knowledge of what makes instructional software effective is still rather limited. We do know that simple transference of conventional printed materials to the computer is not effective, nor are animations or simulations that do not directly engage students’ minds, as noted earlier. The knowledge we have gleaned from studies that led to the interactive engagement (IE) classroom learning strategies apparently also apply to computer-aided learning (CAL). However, simply mimicking IE classroom techniques is unlikely to be the optimum means for CAL. For example, there is good evidence that people vary substantially in their exploratory behavior. One laboratory study[11] showed that “learners with more exploratory behaviors learned significantly faster and scored significantly higher on outcome tests” if they had been assigned to a rule-inductive environment in which they had to induce principles on their own, than if they had been assigned to a rule-application environment in which the software told the learners what the relevant principles were. On the other hand, "less exploratory learners performed significantly better from the more structured, application environment compared to the inductive environment."

In the light of experiments such as this, how can instructional software be made effective for different learning styles? I favor an approach of breaking on-line explanatory/exploratory material into small pieces, each focusing on a single concept, rather than writing larger exploratory programs in the vein of (*e.g.*) Interactive Physics.[12] I refer to these pieces as Physics "Illuminations." They consist of html-readable text, packaged together with a custom Java applet or multimedia component. Such an approach can be helpful to both learning groups mentioned in the preceding paragraph. Less exploratory learners can benefit from the presence of the textual matter of the Illumination, which describes the relevant principle(s), provides instruction in running the applet (for example), and points out noteworthy features. On the other hand, more exploratory learners do not have to read a lot of text prior to engaging in their preferred mode of learning. Indeed, my observations of student use of Illuminations have revealed that some students carefully read all the accompanying text before running the applet, while others just plunge in, trying out different things, occasionally scanning the text for help.

Existing Illuminations

To date I have written something over 40 Illuminations. Although the coverage is still rather spotty, they fall into the following groups:

< One-dimensional kinematics

< Two-dimensional kinematics

< Dynamics

< Vector operations

The large majority are conceptual, and thus may be used in both algebra-based and calculus-based courses. Some are quantitative, dealing with (*e.g.*) the calculation of instantaneous or average velocity or acceleration from kinematics graphs, and some analytical, addressing vector components and sums of forces. Some are demonstrative in nature, but most require student action, and provide visual indication of the correctness of that action. Many keep a running score of correct responses.

The selection of topics reflects my biases and frustrations with conventional texts, as well as my time limitations. For example, texts do not devote sufficient space to the interpretation of graphs for most of my students to learn how to read or sketch a kinematics graph. Many of my kinematics Illuminations were designed to address this deficiency by helping students make a connection between the motion of a physical object (as illustrated with a simulation or a motion diagram, or described in English) and corresponding kinematics graphs, or between graphs of one kinematics variable and a related one.

In learning a concept it often helps to see examples that explore the concept from different directions. Some of my Illuminations utilize this fact. For example, to help students better understand the meaning of position vs. time or velocity vs. time graphs I have created Illuminations that require them to build an English description of the motion represented by a graph, as well as Illuminations requiring the construction of a graph from the English description. To cite another example, I have Illuminations to help students learn to move down the position-velocity-acceleration hierarchy; ones to help them learn the relationships by moving in the other direction are being developed.

Use in Introductory Physics

Although some of my Illuminations can be used for classroom demonstrations (which can be helpful if students are encouraged to think and make predictions about what they see), I believe that they are most useful for student self-study. The question then arises – how do I get students to use the software? Early in the development

I encouraged students to voluntarily work with specific Illuminations to supplement their assigned homework. Although those who did so scored better on subsequent quizzes than their fellow students (well beyond a small self-selection bias), that fact was not sufficient to get most students to use the Illuminations. During the Spring 1999, Fall 1999, and Spring 2000 semesters I assigned many of the Illuminations for homework. Some of the applets keep running scores; these scores were recorded by a simple CGI program, and formed part of their quiz grade. Students were allowed multiple submissions and time to work with the applets for as long as they wished (within a 3-4 day assignment window). To provide additional incentive, some of their daily in-class quizzes and exam questions also tested the material in the on-line homework. Since homework/quizzes counted 40-45% toward their grade, and by putting in the time they could usually get at or near 100% on the on-line quizzes, the participation rate was very high.

By the Fall 1999 semester I had a sufficient number and variety of Illuminations that I spent very little time in class on kinematics graphs and vectors. I did emphasize that the material was important, but said that it could be better learned through practice than by watching me lecture.

This class, which I will refer to as Class A, was small (20 students) and calculus-based. During the Spring 2000 semester I taught two additional sections of the first calculus-based course, which I will refer to as Classes B and C (100 students total). To try to isolate the effect of the Illuminations, I used no interactive engagement teaching techniques in-class for either of these classes. Rather, students were lectured on the material in the traditional manner, although I devoted much more time to conceptual questions in examples, quizzes, and exams than one finds in most traditional classes.

To test the effectiveness of the Illuminations, I administered all or parts of several assessment instruments that have been used nationally to evaluate student learning of mechanics. Classes A and B were given the Test of Understanding of Graphs in Kinematics (TUGK),[13] class A as part of their final exam, and class B as an exam shortly after kinematics instruction. Class C received 7 of the 9 most commonly missed questions on the TUGK as part of their mid-term exam. Furthermore, classes B and C were pre- and post-tested with the Force Concept Inventory (FCI), the former at mid-term, and the latter as part of the final exam. In addition, class B was given the Mechanics Baseline Test (MBT)[14] as part of their final exam.

Results for the percentage scores on the TUGK and MBT are shown in Table 1, along with the average relative gain (g, as defined in Ref. 2) on the FCI. The uncertainties in Table 1 are estimated standard deviations of the mean. For the g-values these standard deviations were estimated by $\sigma_{\bar{g}} = \frac{\sigma_g}{\sqrt{N}}$, where σ_g is the standard deviation of the relative gains for individual students. Previously reported national data is given for comparison. Standard t-tests indicate that the differences between the mean TUGK scores for classes A and B and the national data are statistically significant at better than a 99% level, as is the difference between the FCI g-value for class C and that for traditional classes. The difference between the class B FCI g-value and that for traditional classes is significant at better than a 98% level. The g-values for classes B and C fall solidly within the range for IE classes, despite the fact that no interactive techniques were used with students in-class.

The mean MBT score for class B falls at the low end of the MBT data shown in Ref. 2. However, as pointed out there, MBT scores are highly correlated with post-instruction FCI scores. When the MBT average for class B is compared to the 10 classes whose mean post-instruction FCI score is within 10 percentage points of that class B, one finds that class B's mean MBT score is higher than 8 of these 10 classes (7 of which were IE classes).

The data in the Table 1 strongly suggest that Illuminations can have a substantial positive effect upon student conceptual understanding of introductory mechanics. The data in Table 2 provide further evidence that this is the case. Given in the table are the percentages of students collectively in classes A, B, and C who correctly answered the nine most difficult questions on the TUGK (defined as those for which not even a plurality of students in Beichner's data set answered correctly), along with the similar data reported in Ref. 13. (Unfortunately, the Ref. 13 data do not distinguish the performance of students in calculus-based introductory classes from those in algebra-based or high school classes on individual questions.) The students who worked with the Illuminations did substantially better than the others on 7 of the 9 questions. Moreover, the two questions on which they performed no better deal quantitatively with determining displacement from a velocity graph or velocity change from an acceleration graph – questions in which area is the significant feature. I have not yet written any Illuminations that address this issue. However, many of my students were able to handle questions that require *qualitative* recognition of displacement from a velocity graph, or a velocity change from an acceleration graph, as evidenced by the percentages of correct responses to questions 1 and 10.

Conclusion

Computer-aided supplementary instruction can be a valuable means to help students learn important physical concepts through more productive use of their out-of-class study time. As such, it can be a useful complement to in-class interactive engagement techniques. Perhaps the combination will allow us to help more of our students reach Newtonian mastery.

Try the Illuminations for yourself at **www.uno.edu/~rgreene/illum.html**. The text of the Illuminations is in the public domain and may be modified as desired. The University of New Orleans owns the copyright to the applets; they may be used for non-commercial, educational purposes. Contact me for assistance in using the Illuminations as on-line quizzes. Although the procedure is somewhat awkward at the moment, my near-term intention is to write system software that will simplify administration of Illumination scores. My goal is to produce freely-available, automatically-graded, conceptually-oriented Illuminations that are no more difficult for instructors to handle than are end-of-chapter problem assignments.

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Table 1. Impact of Illuminations upon student conceptual understanding.

	National	**Class A**	**Class B**	**Class C**
TUGK	47% [a]	65% ± 6%	58% ± 3%	
FCI (relative gain)	0.23 , 0.45 [b]		0.32 ± 0.04	0.46 ± 0.06
MBT			49% ± 2%	

[a] As reported for calculus-based classes in Ref. 13.

[b] The first number is the average relative gain reported in Ref. 2 for 14 traditionally-taught high school, college, and university classes. The second number is the average relative gain for 25 university-level interactive engagement (IE) classes.

Table 2. Percentage of correct answers on the most difficult TUGK questions.

TUGK Question Number (Task description)	Ref. 13	Classes A, B, C
1 (Maximum displacement of five velocity graphs)	16	45
4 (Quantitative estimation of displacement from velocity)	28	31
6 (Quantitative estimation of acceleration from velocity)	25	50
8 (English description of a position graph)	37	52
9 (Position graph from an English description)	24	57
10 (Maximum velocity change of five acceleration graphs)	30	46 [a]
16 (Quantitative velocity change from acceleration)	22	22
17 (Quantitative estimation of velocity from position)	21	49
21 (English description of a velocity graph)	18	51 [a]

[a] These questions were not given to students in class C.