# HELPING STUDENTS MASTER CONCEPTS IN MECHANICS BY GRAPHING WITH SPREADSHEETS

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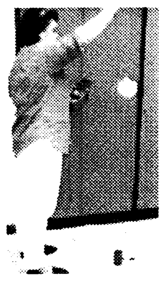
**Abstract**

An example of a curricular activity to help students master concepts in mechanics is presented. Students measure positions and times of movements using calculators, and construct graphs using spreadsheets. Students learn to connect concepts in mechanics and reinforce them following a spiral approach of increasing complexity. Comments from students about the activity are also presented.

## Introduction

At the Colegio Universitario del Este (CUE), in Carolina, Puerto Rico, the physics course has been strongly influenced by the efforts of the Puerto Rico Collaborative for Excellence in Teacher Preparation (PR-CETP) through its Faculty Development Component. Developed through a Minority Science and Engineering Improvement Program (MSEIP) project, this new physics course has benefited from many seminars, workshops, and personal talks where the PR-CETP educational philosophy has been disseminated. The new course, *General Physics I*, was designed for students from the Applied Microbiology Program, who take it mainly during their fourth year in the School of Sciences, Health, and Technology, but it has also been used to teach physics concepts to students from other programs. The course was piloted in 1999 and it has been offered since then. A total of 49 students have benefited from this course. Among the changes made to the teaching format of this course as a result of the PR-CETP project, is the design of the curricular activities based on constructivism in an active learning environment [1,2]. More than ten activities have been used for the first part of the course, which has four units. Improvements in the assessment of the learning/teaching process have also been incorporated. An example of how the students reinforced their understanding of the relation between force and acceleration is presented, as well as the interconnection of related concepts in mechanics. To reinforce their conceptual understanding, the students were guided by means of student activities and the instructor, to make experiments and to collect data. From this data, the students used the basic concept of rate of change to construct position, velocity, acceleration, total force, potential energy, kinetic energy, and total mechanical energy versus time graphs.

## The Experiment: Free Fall Motion



The students use the interface Calculator Based Laboratory (CBL, from Texas Instruments) connected to a calculator and to a motion sensor to collect data on the upward pull of a ball. The picture shows an easy setting for this experiment. A similar setting is used by Sokoloff, Thornton and Laws, but with different interfaces [3]. A rope is attached to a ball, and a motion sensor (bottom right of picture) is placed on the floor below the ball. A sudden pull from the rope makes the ball experience free fall motion. The simplicity of this setup allows repetition of the experiment until good data points are obtained (repetition rates vary from one to four times). Due to the sensitivity of the system to nearby obstacles, the calculator can acquire "noisy" data points that do not correspond to the experiment. Once students learn to remove obstacles that prevent obtaining good results, the data are stored in lists in the calculator's memory and used to construct the position ($x$) versus time ($t$) graph. The calculator also contains programs for automatic graphing of the data from the experiment, but in this course students are taught to construct the graphs by themselves, which is an important part of the learning experience.

Before making the graphs, students are asked to predict the form of these graphs.

## Manipulating the Data

The students are trained on how to manage data from the lists in the calculator and from a spreadsheet. This training is offered in workshops and activities during class. The students can also download this activity from a web page designed for the course [4]. The spreadsheet is useful to give students templates to help them construct the graphs if the emphasis is to be made on the analysis of the graph itself rather than on the construction of the graph. This depends on the particular interests of the instructor according to the curricular sequence of the course. This article focuses on manipulation of data to construct graphs from a spreadsheet.

## Construction of Position vs. Time Graphs

Students construct the $x$ vs. $t$ graph on a spreadsheet. This graph is used to calculate the rate of change relative to corresponding changes in time, which helps students reinforce the concept of velocity.

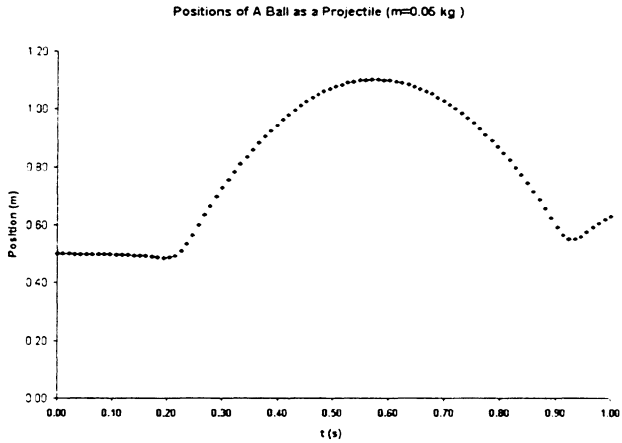



**Figure 1.** Position as a function of time for a ball in free fall.

The $x$ vs. $t$ graph for a typical experiment of a ball in free fall is shown in Figure 1. Students are taught to calculate velocity data through different activities. They learn to write formulas in the cells of a spreadsheet using $x$ and $t$ data; e.g., if the positions of the ball are placed starting from the 3rd row of column B [see Appendix] and the corresponding times start from the 3rd row of column A, then the formula for velocity to be entered at the beginning of the column of the velocities should be (B4-B3)/(A4-A3). This is how the first velocity is calculated and the remaining velocities can be easily obtained likewise for the remaining $x$ and $t$ values.

## Construction of Velocity Graphs

When the students compare the actual graphs with the ones they predicted, they understand the need to replace their previous knowledge with the new knowledge they construct by themselves from a concrete experience such as this. By graphing the velocity of the ball (see Figure 2), students realize the vectorial nature of the velocity. When making velocity and acceleration calculations, students are guided to recognize the cumulative error that is introduced, but no treatment is performed in order to preserve simplicity and emphasize conceptual understanding.

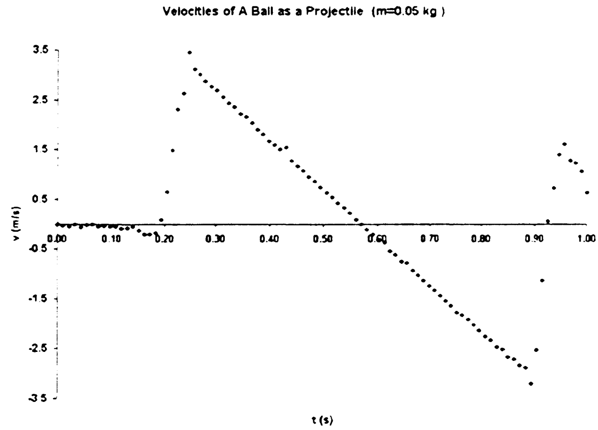



**Figure 2.** Velocity as a function of time for a ball in free fall.

However, correct manipulation of these graphs does not mean conceptual understanding, as revealed through assessment questions made to students. For example, when asked to interpret graphs in paper and pencil exercises, students sometimes failed to give correct interpretations, although they were guided to interpret and describe the movement from these graphs. However, making and interpreting graphs are among the deficiencies exhibited by students in this course. These difficulties have also been reported by Beichner [5]. Resistance to change prior conceptual structures by students has been reported by physics professors such as McDermott and others from the University of Washington [6], and Redish and Steinberg from the University of Maryland [7].

## Construction of Acceleration Graphs

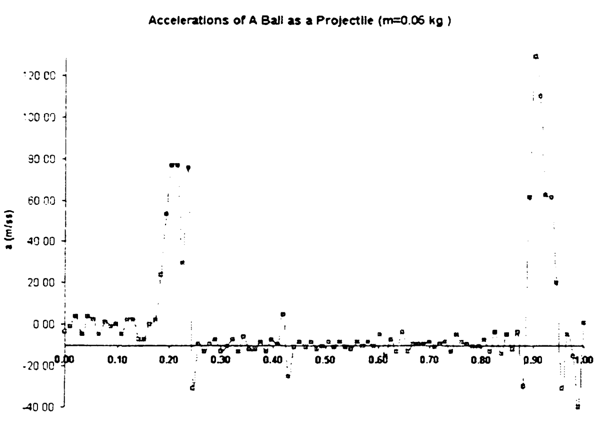



**Figure 3.** Acceleration as a function of time for a ball in free fall.

When students construct the acceleration graph on the rise and fall of the ball, they are aware of the constancy of its acceleration and that the acceleration is not the velocity of the ball, a common misconception held by students in this course as noticed from their assignments, diagnostic questions, and tests; similar errors were also reported by McDermott [6], Arons [8], and Thornton [9]. Students also compared their predictions on the acceleration of the ball at its highest point; the acceleration vs. time graph allowed them to visualize that the acceleration of the ball remained the same during the time it is in free fall, even at the time the ball is momentarily at rest at the highest point of its trajectory.

## Construction of Force Graphs

From acceleration and force data from other experiments, students learned the relation between force and acceleration (Newton's Second law).

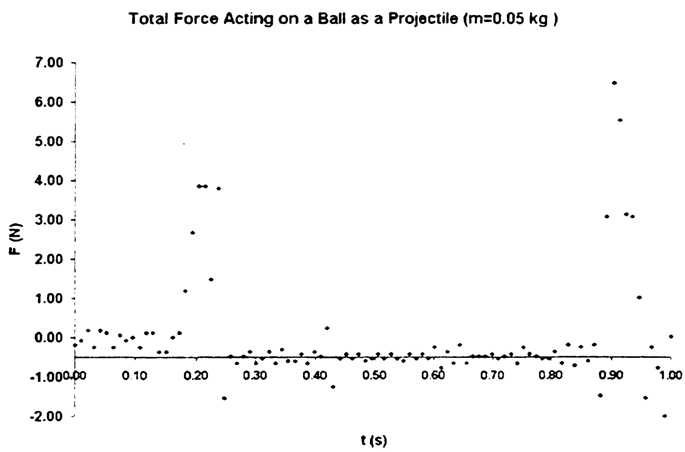



**Figure 4.** Total force as a function of time for a ball in free ball.

Students enter this relation as an equation in another cell of the spreadsheet and generate total force data for the experiment. From this graph, students reinforce their understanding of the relation between force and acceleration when they observe both graphs having the same shape, differing only in scale by a factor equal to the mass of the ball. Students also studied the impulse given to the ball from these graphs.

## Construction of Kinetic Energy Graphs

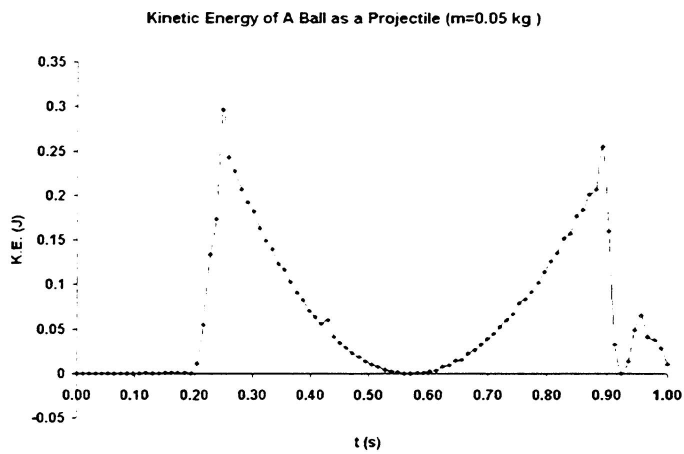



**Figure 5.** Kinetic energy as a function of time for a ball in free fall.

Students were motivated to use the relation between energy and Newton's Second law with other curricular activities, in order to generate data tables for the potential and kinetic energies as a way to guide them to conservation of energy. They used the same procedure of entering the equation in a cell of the spreadsheet.

After reinforcing their mathematical skills of squaring functions, students finally constructed the kinetic energy graph (see Figure 5).

## Construction of Potential Energy Graphs

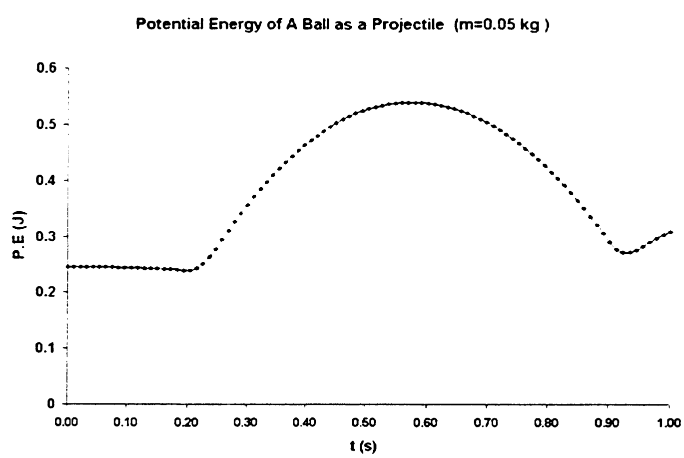



**Figure 6.** Potential energy as a function of time for a ball in free fall.

Following the same procedure explained above, the students construct a graph on the potential energy of the ball. They obtain a graph similar to an inverted version of the kinetic energy graph for the time the ball is in free fall.

## The Total Mechanical Energy of the Ball in Free Fall

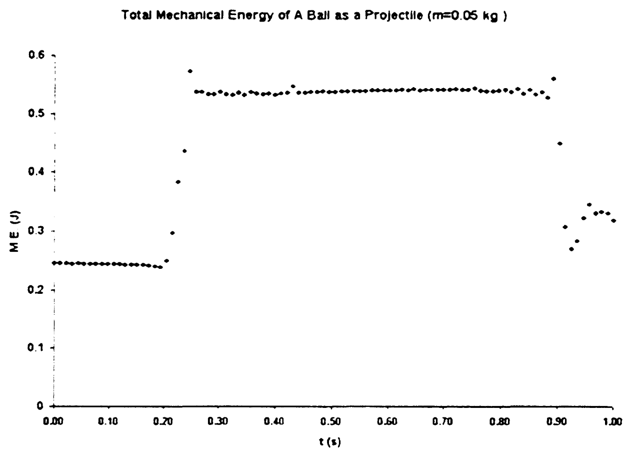



**Figure 7.** Total mechanical energy as a function of time for a ball in free fall.

When students compare the two energies for the free fall of the ball, they visualize the relation between them. Having visualized this, they add the two energies in a separate cell of the spreadsheet and graph the total energy vs. time. The students discover that this sum is constant while the ball is in free fall. This way, they were guided to the concept of conservation of energy. They have never been told about conservation until this moment. And, they do this by being actively involved in an experiment and trying out the calculations by themselves.

## Assessing Conceptual Understanding

Conceptual understanding of students in this activity was assessed by means of pre- and post-tests, diagnostic and follow-up questions designed by the instructor. These tests were based on strategies modeled mainly by CETP and FIPSE workshops on preparing items for exams and on the format used by the Puerto Rico College Board. No use of standardized tests (Force Concept Inventory, etc.) was made, but elements from these tests were incorporated (i.e., selection of topics and format). Since this is a new course, there is no previous history on students' grades that allows adequate comparison with the results drawn from this course (to date, this course has been offered three times, once as a pilot course). Preliminary results are published on the course website [10] and show that the students have increased an average of 75% in the total earned points for selected concepts from the post-test as compared to the pre-test (the test contained questions on nineteen concepts, the concepts selected were five). Results on the complete test also revealed that the increment in points earned was 84% higher for post-test than for pre-test. Students also expressed their feelings about the experiments, activities, and the methodology used in class. In general, the students felt comfortable with the methodology, and expressed being pleased with the activities used in the class through which they could discover concepts in an interesting way. A collection of student perceptions before and after the class, as well as general comments, can be read from the course website and are summarized below. Although the selected concepts inventory increased learning, the total test revealed that students did not progress on nearly ten concepts. These results are being used to redesign the activities and to evaluate the methodology used.

**Summary of Student Comments**

Students were asked about their experience with the activities and the strategy used in class. Some comments from students are presented below, while a complete list of comments appear on the course website. Students wrote their responses to the following questions: 1. Indicate what you liked or disliked about this course; 2. What would you recommend about this course to students coming to the course next year?; 3. What would you change about this course?

- "The course is very good and the professor is very dynamic and enthusiastic."
- "This course is good since you offer many activities and demonstrations, and you are not at the blackboard but with us, i.e., it is interactive."
- "The good part about the course is that I have learned a lot since the class is dynamic, the bad part is that I am not familiar with computers."
- "This course is very good, but sometimes you get excited and go so fast that I get lost. Besides that it is very good, the way the concepts are explored is the most interesting way because we see the concepts and then we discover what is in there. That is really fun, and so we learn."
- "The good part of this course is that everything is done on the basis of exploration of the concepts. For example, we do experiments first to discover Newton's laws, and then we do different applications."

- "I would tell the students that the class is very interactive. I love the class and we learn everything in a different manner. Is one of the best classes I have had."
- "They [the activities] are very good and clarify doubts in what you need to learn or improve, however sometimes some of these activities have concepts that are a little hard or complicated."

**Recommendations**

Although the students showed good performance in manipulating graphs from spreadsheets, this does not guarantee that they improved their conceptual understanding dramatically. Reinforcement of the concepts should be promoted through repetition of similar activities in new contexts, as explained by McDermott [11]. Follow-up questions that assess transference of the concepts to new situations should be offered as much as possible. Workshops on how to use computers, calculators, etc. should also be incorporated into the curricular design from the very beginning to help students with these technological skills. Continual guidance from instructor and improvement on teaching strategies should be used to overcome these difficulties.

The students from the Middle Sciences Education Program at CUE will be taking this course in the year 2001. This academic program is also a new offering and no history is available about student performance on physics courses, but a hope is maintained for producing a positive impact on these future science teachers.

**Conclusions**

Inclusion of the constructivist vision and philosophy of PR-CETP has been incorporated into the design of a new course in physics. Activities that incorporate technological applications should be offered to students with adequate support through additional activities such as seminars, workshops, related readings and others, to avoid technological anxiety. Also, continual intervention and guidance from the instructor is needed due to the complexity of the technological setting that sometimes overshadow the conceptual understanding. However, the active environment used in this course generally increased their motivation and interest toward the course. The use of spreadsheets is very convenient for studying concepts in dynamics and serves to assess the whole picture of students' understanding. Due to the fact that the graphs are strongly correlated, this strategy provides students with visual images of the interconnections of the concepts studied. Although the results drawn from this course are not comparable with previous year results due to the absence of history, this course has shown some improvement in conceptual understanding in physics concepts and also will be impacting students from the Middle Sciences Education Program at CUE. ■

## Appendix

The table appearing below shows an example of the formulas used to calculate velocity in *Excel*. Results are shown up to the eighth $x$, $t$ data pair. Formulas appear at the right of the table. Once the formula for calculating the first velocity ($v$) is entered in the corresponding cell of column C of the spreadsheet, the remaining velocities can be easily calculated by pressing over the right down corner of this cell (this command works when the column located at left of column C of the spreadsheet is complete). This formula can be entered in this cell by writing the following command: = (B4-B3)/(A4-A3). Here B is the cell for positions $x$, A is the cell for times $t$, and C is the cell for velocities $v$. The acceleration, force, potential energy, etc., are entered similarly as shown in the table.

**Positions and times for a free fall**

| t (s) | x (m) | v (m/s) | a (m/ss) | Ft (N) | x(m) | EP (J) | EC (J) | EP+EC (J) | m (kg): | Equations for: | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.00 | 0.50 | 0.00 | -3.56 | -0.18 | 0.01 | 0.25 | 0.00 | 0.25 | 0.05 | v | =(b4-b3)/(a4-a3) |
| 0.01 | 0.50 | -0.04 | -1.19 | -0.06 | 0.01 | 0.25 | 0.00 | 0.25 | a (m/ss) | a | =(c4-c3)/(a4-a3) |
| 0.02 | 0.50 | -0.05 | 3.56 | 0.18 | 0.01 | 0.25 | 0.00 | 0.25 | 9.8 | F | =0.05*a |
| 0.03 | 0.50 | -0.01 | -4.76 | -0.24 | 0.01 | 0.25 | 0.00 | 0.25 | | EP | =0.05*a*(a3:a96) |
| 0.04 | 0.50 | -0.06 | 3.56 | 0.18 | 0.01 | 0.24 | 0.00 | 0.25 | | EC | =0.5*0.05*(c3)^2 |
| 0.05 | 0.50 | -0.03 | 2.38 | 0.12 | 0.01 | 0.24 | 0.00 | 0.24 | | EMT | =EC+EP |
| 0.06 | 0.50 | 0.00 | -4.75 | -0.24 | 0.01 | 0.24 | 0.00 | 0.24 | | | |
| 0.08 | 0.50 | -0.05 | 1.19 | 0.06 | 0.01 | 0.24 | 0.00 | 0.24 | | | |

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