AC 2012-3346: INTEGRATING REAL WORLD ENGINEERING EXAMPLES AND MATHEMATICAL CALCULATIONS INTO COMPUTER SIMULATIONS TO IMPROVE STUDENTS' UNDERSTANDING OF CONCEPT PAIRS

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Integrating Real-World Engineering Examples and Mathematical Calculations Into Computer Simulations to Improve Students' Understanding of Concept Pairs

Abstract

Submitted for the "works in progress" (poster) track of the K-12/Pre-college Division, this study is an ongoing collaborative effort between a university engineering educator, his undergraduate student researcher, and a high school physics teacher. The goal of the study is to develop a unique set of computer simulation modules to improve students' understanding of concept pairs in high school physics, specifically in Newtonian mechanics. A concept pair is a pair of physics concepts that are fundamentally different but closely related. The unique computer simulation modules combine three features. First, real-world engineering examples are integrated into computer simulations to make student learning relevant and meaningful. Second, mathematical calculations are integrated into computer simulations, so students can connect physics concepts with mathematical equations to understand each concept pair in greater depth. Third, computer simulations are interactive and require students' inputs to promote active learning.

This paper presents the computer simulation module that we recently developed for and implemented in a high school physics course. The computer simulation module focuses on improving understanding of three important concept pairs: linear displacement and angular displacement, linear velocity and angular velocity, and linear acceleration and angular acceleration. A total of 15 high school students participated in the study. A pretest and a posttest, each consisting of 12 test items, and a questionnaire survey were administrated to assess student learning gains. The results showed that students achieved an average learning gain of 46.7-71.4%. Students also reported positive experiences with the developed computer simulation module.

Introduction

High school physics covers numerous fundamental concepts that students must understand and master to succeed in undergraduate science or engineering curriculum. For example, Newtonian mechanics (a branch of physics) involves foundational concepts such as displacement, velocity, acceleration, force, torque or moment, work, energy, impulse, momentum, and vibrations, as well as foundational laws and principles such as Newton's laws, the Principle of Work and Energy, and the Principle of Linear Impulse and Momentum [1-3]. Lacking a solid understanding of these foundational concepts, laws, and principles is is one of the main reasons many high school students perform poorly in physics [4-6].

Many high schools have adopted innovative instructional strategies such as in-class demonstration, multimedia, and computer simulations, to improve students' understanding of physics concepts [7-9]. A significant amount of educational research has demonstrated the effectiveness of these instructional strategies, particularly computer simulations [10-12], in improving student learning. For instance, Maria and Romuald [11] stated that "computer simulation enables students to model and study physical phenomena in a situation when it is impossible to carry out research, for example, because of time, safety requirements or lack of proper instruments." More importantly, from the education psychology viewpoint, computer simulations "create an atmosphere in which students may initiate actions, learn how to be more independent, analyze and make conclusions." [11]. Through carefully-designed educational experiments that included control and experimental groups in secondary school physics classes, Maria and Romuald [11] found that computer simulations improved students' understanding of physical phenomena as well as analytical and creative thinking skills.

In another study, Zacharias and Anderson [12] investigated the effects of computer simulations on students' conceptual understanding of physics, specifically mechanics, waves/optics, and thermal physics. They presented computer simulations to the students prior to performing real-world laboratory experiments. Through pre-post conceptual tests and semi-structured interviews, Zacharias and Anderson [12] found that computer simulations helped students predict and explain the physical phenomena in subsequent real-world laboratory experiments, and that computer simulations fostered a significant conceptual change in relevant physics content areas.

It must be pointed out that nearly all exiting physics education efforts (such as the published literature [7-12]) focus on improving students' understanding of individual concepts, but not concept pairs. *A concept pair is a pair of physics concepts that are fundamentally different but closely related*. For example, linear acceleration and angular acceleration is a concept pair. Linear acceleration, in the units of m/s^2, is used to quantify the change of linear velocity (m/s) with time. Angular acceleration, in the units of rad/s^2, is used to quantify the change of angular velocity (rad/s) with time. There exists a quantitative mathematical relationship between linear (tangential) acceleration and angular acceleration. Without understanding the fundamental difference and relation between the two concepts of a concept pair, students cannot select the correct concept required to accurately interpret a particular physics phenomenon or to solve a particular physics problem. In other words, students will not know when and why to apply each concept and its associated equations to solve physics problems.

Submitted for the "works in progress" (poster) track of the K-12/Pre-college Division, this study is an ongoing collaborative effort between a university engineering educator, his undergraduate student researcher, and a high school physics teacher. The goal of the study is to develop a unique set of computer simulation modules to improve students' understanding of concept pairs in high school physics, particularly in Newtonian mechanics. The unique computer simulation modules combine three features. First, real-world engineering examples are integrated into computer simulations to make student learning relevant and meaningful. Second, mathematical calculations are integrated into computer simulations, so students can connect physics concepts with mathematical equations to understand each concept pair in greater depth. Third, computer simulations are interactive and require students' inputs to promote active learning.

This paper presents the computer simulation module that we recently developed for and implemented in a high school physics course. The computer simulation module focuses on improving understanding of three important concept pairs: linear displacement and angular displacement, linear velocity and angular velocity, and linear acceleration and angular acceleration. A total of 15 high school students participated in the study. A pretest and a posttest, each consisting of 12 test items, and a questionnaire survey were administrated to assess student learning gains. The results showed that students achieved an average learning gain of

46.7-71.4%. Students also reported positive experiences with the developed computer simulation module.

A Real-World Engineering Example

Incorporating engineering examples into K-12 science and mathematics course curricula has been proven to be an effective instructional strategy that helps students understand the real-world applications of science and mathematics concepts [13-15]. The first author of this paper has nearly 30 years experience in the engineering research field, particularly in the area of metal machining. Therefore, a real-world engineering example that involves the process of metal machining was selected for use in the computer simulation module. A flash video clip from his machining research laboratory was incorporated into the computer simulation module, as shown in Figure 1. The engineering example demonstrated by the video clip involves the rotational motion of a cylindrical workpiece that is being machined by a cutting tool insert. Fundamental physics concepts – such as displacement, velocity, and acceleration – are addressed in this engineering example. Students could watch the online video clip (with audio) to understand the engineering context in which the computer simulation module was developed.

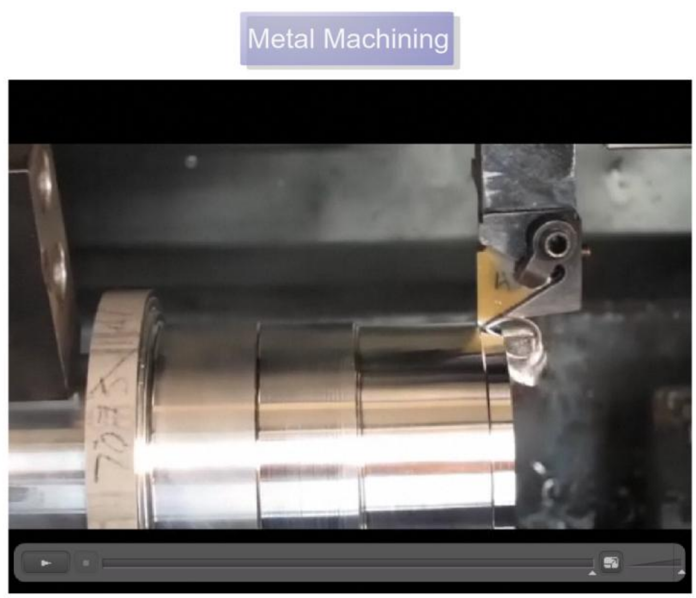

Figure 1. A flash video clip that shows the process of metal machining

Development of the Computer Simulation Module

Displacement, velocity, and acceleration are fundamental physics concepts that play a critical role in student learning of Newtonian mechanics. The learning objective of our computer simulation module is to develop a solid understanding of fundamental differences and relationships between the concept pairs of:

- Linear displacement (m) and angular displacement (rad)
- Linear velocity (m/s) and angular velocity (rad/s)
- Linear acceleration (m/s^2) and angular acceleration (rad/s^2)

Figures 2-5 show four major computer user interfaces (CUIs) of the computer simulation module. On each CUI, students can move the tool bars (see those shown in Figs. 2-5) to change the values of three inputs:

1) Spindle and workpiece maximum rotational speed n (rpm)
2) The time t_s (seconds) for the spindle to rate at a constant angular acceleration from rest to its maximum rotational speed
3) Workpiece diameter D (mm) or radius r (mm)

The CUIs in Figs. 3-5 provide all necessary mathematical equations and show how displacement, velocity, and acceleration *simultaneously* change when students move the tool bars to change input values. The equations that relate linear displacement to angular displacement ($S = r \cdot \theta$), relate linear velocity to angular velocity ($v = r \cdot \omega$), and relate linear acceleration to angular acceleration ($a_t = r \cdot \alpha$) are also highlighted and shown in the middle of each CUI in Figs. 3-5.

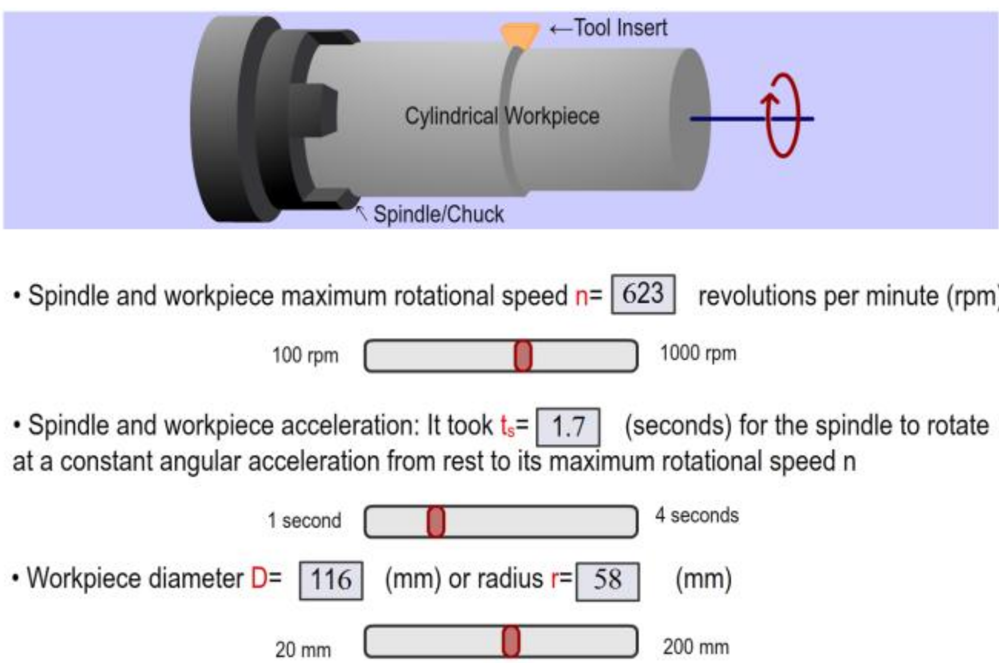

Figure 2. The developed computer simulation module: Computer User Interface #1

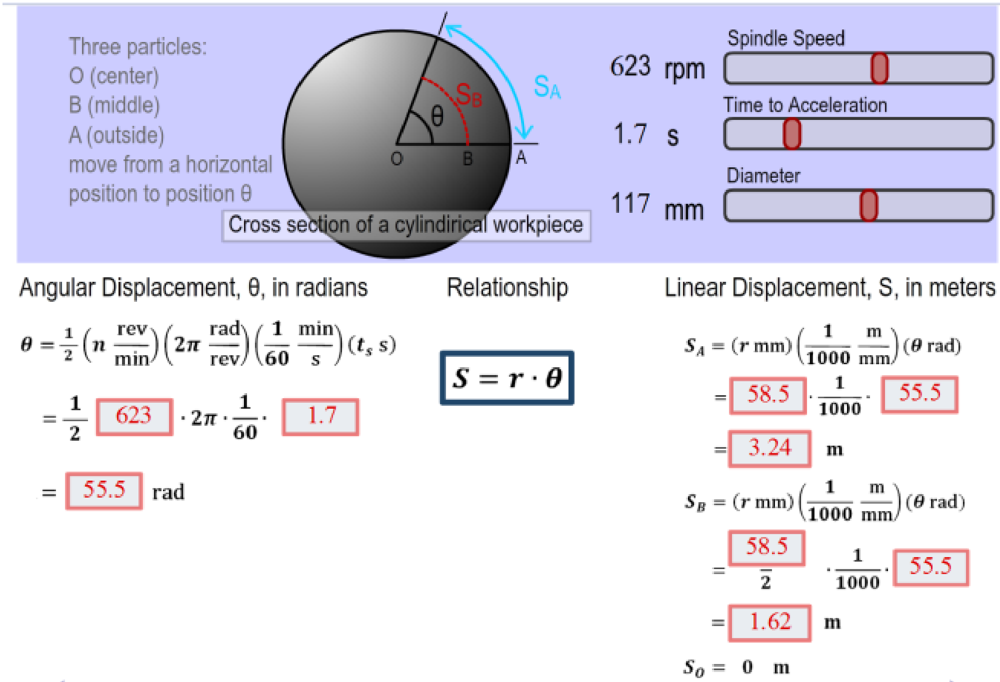

Figure 3. The developed computer simulation module: Computer User Interface #2

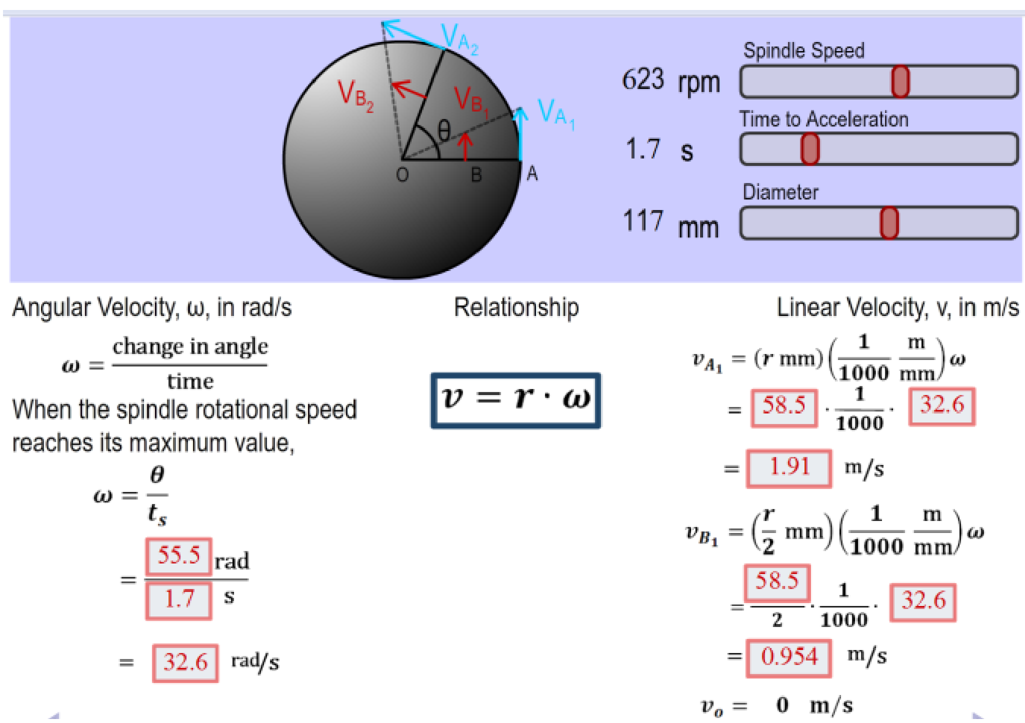

Figure 4. The developed computer simulation module: Computer User Interface #3

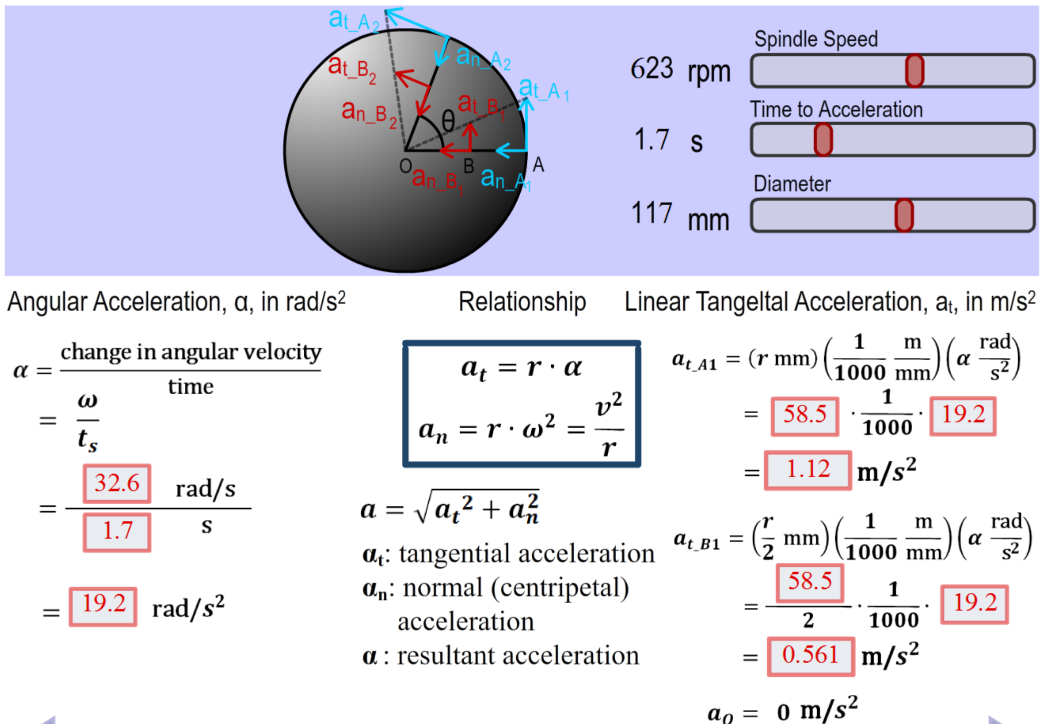

Figure 5. The developed computer simulation module: Computer User Interface #4

Students were asked to do the following tasks:

1. Change t_s (the time for the spindle to rotate from rest to the max rotational speed) five or more times while keeping both n (the spindle's max rotational speed) and D (the diameter of the workpiece) constant.
2. Write down the values of θ, S, ω, v, α, and a_t for each t_s tested in step 1.
3. Generate Excel graphs for θ vs S, ω vs v, α a_t s at for particle A, particle B, and particle O, respectively.
4. Answer the question: What observations do you make from the Excel graphs you made in step 3?
5. Answer the questions: AFTER the spindle reaches its maximum rotational speed and rotates at that constant speed, what is the angular acceleration (α) of the spindle? What will the linear acceleration (a_t and a_n) will be? Explain why.

Pretest and Posttest to Assess Student Learning Gains

The computer simulation module described above was implemented in a high school physics course. A total of 15 junior high students, including nine female and six male students, participated in the study. Based on the real-world engineering example described before, a technical problem that included 12 test items was developed for use in the pretest and posttest to assess student learning gains. The following equation [16] was used to calculate the learning gain for each question:

$$\text{Learning gain} = \frac{\text{Posttest score (\%) - Pretest score (\%)}}{\text{100 (\%) - Pretest score (\%)}} \quad (1)$$

The technical problem that included 12 test items is described in the following paragraphs:

As shown in the following Fig. 6, particles A and B are on the circumference and the middle, respectively, of a circular disk. Each particle has a mass of 0.002 kg. The disk has a radius of 100 mm. It takes two seconds, at a constant angular acceleration, for the disk to rotate from rest to the rotational speed of 400 revolutions per minute.

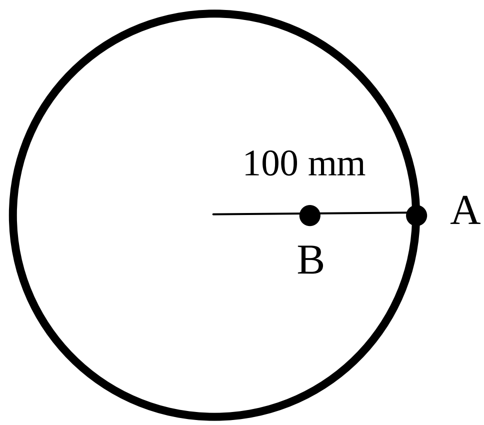

Figure 6. The technical problem for use in the pretest and posttest to assess student learning gains

1. Over 2 seconds, the linear displacement of particle A is ____________ meters.
2. Over 2 seconds, the linear displacement of particle B is ____________ meters.
3. Over 2 seconds, the angular displacement of particle A is ____________ radians.
4. Over 2 seconds, the angular displacement of particle B is ____________ radians.
5. At the end of 2 seconds, the linear velocity of particle A is ____________ m/s.
6. At the end of 2 seconds, the linear velocity of particle B is ____________ m/s.
7. At the end of 2 seconds, the angular velocity of particle A is ____________ rad/s.
8. At the end of 2 seconds, the angular velocity of particle B is ____________ rad/s.
9. At the end of 2 seconds, the linear tangential acceleration of particle A is ____________ m/s^2.
10. At the end of 2 seconds, the linear tangential acceleration of particle B is ____________ m/s^2.
11. At the end of 2 seconds, the angular acceleration of particle A is ____________ rad/s^2.
12. At the end of 2 seconds, the angular acceleration of particle B is ____________ rad/s^2.

If a student provided a correct answer to a test item, the student earned one point; otherwise the student earned zero points. In cases where a student's answer was incorrect due to the wrong convention of units, partial credit (0.5 points) was given to the student.

The pre-test was completed two days before the students run the computer simulation program. One laboratory session (1.5 hours) was dedicated for the students to run and learn from the computer simulation program. The post-test was implemented three weeks later.

Table 1 summarizes the results of pretest and posttest and student learning gains. As seen from Table 1, the students scored zero or nearly zero on all test items in the pretest. The learning gains for all students averaged between 46.7% (for test item No. 12) and 71.4% (for test item Nos. 1 and 2).

Table 1. The results of pretest and posttest and student learning gains

Test item number	Pretest		Posttest		Average learning gain (%)
	Average	Standard deviation	Average	Standard deviation	
1	0.07	0.26	0.73	0.37	71.4
2	0.07	0.26	0.73	0.37	71.4
3	0	0	0.70	0.41	70.0
4	0	0	0.53	0.48	53.3
5	0	0	0.63	0.40	63.3
6	0	0	0.63	0.40	63.3
7	0	0	0.60	0.39	60.0
8	0	0	0.50	0.42	50.0
9	0	0	0.63	0.40	63.3
10	0	0	0.63	0.40	63.3
11	0	0	0.57	0.42	56.7
12	0	0	0.47	0.44	46.7

Questionnaire Survey

A questionnaire survey was also administered after the posttest. Students were asked to provide feedback on the following statements: "Please describe to what extent the computer simulation helped, or did not help, with your understanding of physics concepts; and, please describe to what extent the computer simulation helped, or did not help, with your understanding of mathematical calculations." The students reported positive experiences with the developed computer simulation module. Representative student comments (original, without editing) are listed below:

- "The modules illustrated a real-world application for the concepts that helped me see what I was applying the concepts to. Seeing the diagram of each concept was useful in showing how each piece of a formula fits into the big picture."

- “The computer simulation aid help me understand the physics concepts, because of the preliminary video we viewed, and the adjusting bars of speed, size and rotation. This helped me understand what parts of the equation was being calculated, where to plug them in, and how to solve for the missing variable.”

- “I really began to remember from learning MIS previously. But this time, rather than just memorizing formulas, the module really helped me understand the why.”

- “I got to see all the numbers right in front of me without screwing up the calculations myself. I went from having no idea what I was doing to being able to predict the effects of changing variables. This helped me to imagine the concepts at work.”

- “It showed what values were being put into the equations, which was helpful, and it showed what happens when a value is changing, which helped me understand the relationships between the concepts.”

- “The concepts were labeled on the diagrams, which I found helpful. It was much easier to see where things came from once I understood the difference between linear and angular displacements, velocities, and acceleration.”

- “The computer modules helped me see how to do the calculations. It was really helpful to see all the steps on one screen, with the formulas at the top of the page.”

Limitation of the Present Study and Future Work

The present work-in-progress study has one limitation: It did not include a control group. In ideal cases, the effectiveness of computer simulations on student learning should be validated through experiments that involve both experimental and control groups. However, due to our curricular design, it is impractical to divide a class of 15 students into an experimental group and a control group for educational research purposes. To be practical, we are considering conducting quasi-experiments in our future work to further validate the effectiveness of the computer simulation program developed. Students in one semester would use the developed computer simulation program and would be treated as the quasi-experimental group. Students in another semester would not use the developed computer simulation program and would be treated as the comparison group.

The second limitation of the present study is its small sample size: Only 15 students were involved. In the future work, the computer simulation program developed will be tested in other high school settings that involve large sample size. The large size sample would also allow the researchers to investigate the effects of student characteristics, such as learning styles, motivation, meta-cognition, prior academic achievement, and ages and races, on student learning gains. Collaborations are expected to occur among engineering and science educators, learning specialists, and education psychologists.

Conclusions

Nearly all existing physics education efforts focus on improving students' understanding of individual concepts, but not concept pairs. This paper presents a unique computer simulation module recently developed for, and implemented in, a high school physics course to help students understand three important concept pairs. The developed computer simulation module has three features: incorporating a real-world engineering example into computer simulations, integrating mathematical calculations into computer simulations, and offers interactive learning experiences for students. The pretest and posttest results show that students achieved an average learning gain of 46.7-71.4% on posttest questions. The questionnaire survey results also show that students had positive experiences with the developed computer simulation module.

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