

High School Physics: An Interactive Instructional Approach that Meets the Next Generation Science Standards

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Improving high school physics teaching and learning is important to the long-term success of science, technology, engineering, and mathematics (STEM) education. Increasing our national STEM literacy and workforce readiness includes intensifying and diversifying student participation in STEM learning experiences. Efforts are currently in place to develop an understanding of science among high school students through formal and informal educational experiences in engineering design activities emphasizing the science and engineering practices included in the Next Generation Science Standards (NGSS) framework (NGSS Lead States, 2013).

The Next Generation Science Standards (NGSS) framework has indicated the importance of the engineering design process in K-12 education. The framework was developed in an effort to produce K-12 science standards rich in content and practice and coherent across disciplines (NGSS Lead States, 2013). These standards have been divided into different areas and by disciplinary core ideas. One of the core ideas for grades 9-12 indicates that students should be able to “plan and conduct an investigation to provide evidence that an electric current can produce a magnetic field and that changing a magnetic field can produce an electric current” (NGSS Lead States, 2013, p. 253). Furthermore, the NGSS (2013) indicates that engineering must be a fundamental part of the new framework since students are required to develop the capability to carry and transfer knowledge across science disciplines through modeling, planning, conducting investigations, analyzing and interpreting data, and constructing explanations to demonstrate understanding of the science core ideas. Students must be able to “apply scientific ideas to solve a design problem, taking into account possible unanticipated effects.” (NGSS Lead States, 2013, p. 254). The NGSS, along with the Technology and Engineering Literacy Framework for the 2014 National Assessment of Educational Progress, recommend the integration of engineering and science in K-12 education. The integration and implementation of engineering design activities to the K-12 curriculum has shown that it provides a venue for students to learn relevant STEM content (Hmelo, Holton & Kolodner, 2000; Householder & Hailey, 2012;

Schunn, 2008). Moreover, experimental studies have shown that students become more motivated or engaged when they relate a STEM concept/principle to a real world problem (Adams et al., 2008). It is through engineering design that students are able to see the applicability of abstract and somewhat intangible concepts. In addition, students are able to make connections across disciplines and provide improved solutions to specific problems. Students are able to recognize that certain criteria need to be prioritized, distinguish the range of criteria and constraints, and test the validity of their solutions by comparing to the real world (NGSS Lead States, 2013). Learning difficult concepts while working toward an objective (i.e. solving the engineering design problem) allows students to see how possible solutions can be tackled with engineering methods.

This article investigates physics learning and teaching research and the use of engineering design in the teaching of physics. By integrating engineering into STEM, students may apply scientific ideas to solving an engineering design problem while carrying and transferring knowledge in core science areas.

The Predicament of High School Physics

High school physics, which “marks the final stage of high school science” (Sadler & Tai, 2000, p.111), is a useful preparation for students who plan to pursue college science and engineering because it introduces fundamental concepts such as force and motion, thermodynamics, fluids, and electric circuits (Sadler & Tai, 2000; Tyson, Lee, Borman, & Hanson, 2007). It is suggested that students should master “sufficient knowledge of science and engineering to engage in public discussions on science related issues” because science and engineering “permeate every aspect of modern life” (National Research Council, 2011, p. 1). Data from a national survey in 2011 showed that 74 percent of Americans thought, “STEM education is very important” (Lerner, Goodenough, Lynch, Schwartz, Schwartz, & Gross, 2012). However, it has become common for high school students to avoid basic physics because learning physics is a difficult pursuit (Huffman, 1997). Few students have functional understanding

of the concepts they have studied (McDermott, 2001). Some common mistakes recognized by high school physics teachers include misconceptions on the effects of an electric field on charges, magnetic field lines, and Newton’s Law in electromagnetic context (Aubrecht & Raduta, 2005; Planinic, 2006; Saglam & Millar, 2006).

Misconceptions are prevalent in physics because traditional teaching methods are not effective in helping students correctly and comprehensively understand different scientific concepts. This can occur for a variety of reasons, but one of the primary reasons can be that everyday experiences can provide evidence that supports incorrect assumptions (Stein, Larrabee, & Marman, 2008). Misconceptions are stable cognitive structures that can change, affect students’ understanding of scientific concepts, and must be overcome so that students learn scientific concepts effectively (Hammer, 1996). Misconceptions are found in several areas of physics. For instance, in dealing with electric circuit, students often confuse related concepts such as current, voltage, energy and power. Besides, students often misinterpret schematic representations and fail to grasp the electric circuit as a system (Bagno & Eylon, 1997). In the area of mechanics, one of the major challenges is that the correct understanding of its laws requires a radical change in the way of thinking to successfully make the transition to Newtonian thinking. Students already have a vague system of beliefs about the physical world, loosely based on their empirical experience, which is often wrong but deeply rooted in their way of thinking (Martin-Blas, Seidel, & SerranoFernandez, 2010).

Studies showed that one frequent misconception among students in physics is how to interpret, describe, and represent field lines. In electromagnetism, an investigation showed that hierarchical sequence between concepts is not fully understood mostly due to confusion by representation, which causes a misconception about force concepts (Tornkvist, Pettersson, & Transtromer, 1993). Conceptual understanding of field lines is very important when learning physics, especially electromagnetism. According to the Comprehensive Conceptual Curriculum for Physics (C3P) research based curriculum developed at the Department of Physics at the University of Dallas,

the misconception that magnetic fields are not three-dimensional (3D) and that there is a finite number of field lines appeared on the list of misconceptions that high school teachers have recognized in their students (Comprehensive Conceptual Curriculum for Physics, 2009). Misconceptions are not limited to children. Misconceptions are also maintained throughout high school and into college (Stein et al., 2008). Therefore, it is important to address the misconceptions in electromagnetism, such as field lines, through different methods in order to better prepare students and teachers in this area.

One method that shows promise in addressing misconceptions is improved spatial visualization. Spatial visualization skills are vital to success in many fields of STEM and a variety of other careers (Ault, & John, 2010; Contero, Naya, Company, Saorin, & Conesa, 2005; Contero, Company, Saorin, & Naya, 2006; Strong & Smith, 2001; Sorby, 2001; Veurin, Hamlin, Kampe, Sorby, & Blasko, 2009). Spatial visualization skills are defined as “the ability to manipulate an object in an imaginary 3D space and create a representation of the object from a new viewpoint (Strong & Smith, 2001, p.2).” The abilities to recognize as well as mentally manipulate the spatial configurations are two major categories of spatial factors.

However, lacking 3D visualization skill has become one of the major problems that impacts students’ success in engineering and technology fields (Veurink et al., 2009). Studies at Michigan Tech (Sorby, 2007) found that approximately 20% of the freshman engineering students had scores below 60 (out of 100) on the Spatial Visualization Test designed by Purdue University. Students who lack the spatial visualization ability usually have difficulties in abstracting 3D information from 2D representations of objects and developing an understanding of the concepts (Osborn & Agogino, 1992). There is a need to enhance students’ spatial visualization skills. It is believed that 3D simulation models can impact spatial ability because they enhance students’ understanding “by providing a degree of reality unattainable in a traditional twodimensional interface” and creating an interactive learning environment” (Kim, Park, Lee, Yun, & Lee, 2001; Korakakis, Pavlatou, & Spyrellis, 2009; Lee, Park, Kim, & Lee, 2005; Strong & Smith, 2001) Kim et al. (2001) conducted a series of studies to investigate the impact of 3D simulations in science education. One of the studies assessed the effectiveness of interactive 3D simulations in learning Physics concepts by involving three groups of junior high school students. The results showed that students who used the interactive 3D simulations gained significant improvement in academic achievement compared to those who didn’t use 3D simulations. Results indicated that interactive 3D simulations could enhance middle school students’ conceptual development of the basic science phenomena.

Engineering design activities are effective in improving the teaching and learning of physics in terms of student academic achievement and their learning attitude

(Cantrell, Pekca, & Ahmad, 2006; Dym, Agogino, Eris, Frey, & Leifer, 2005). Mentzer (2008) stated that introducing engineering design appears to improve students’ learning, satisfaction, and retention in STEM fields. Mentzer (2008) also indicated that “learning techniques associated with engineering design challenges are successful in improving student achievement” (p. 31). Adams et al. (2008) indicated that by relating to the real world and using suitable animation and interactivity, the desired curiosity is encouraged and students are more easily engaged in the exploration of topics that include relatively unfamiliar science. Incorporating engineering design activities to physics instruction, such as designing “a toy that converts the mechanical energy of motion into electricity” (Eisenkraft, 2010, p. 780–781), could allow students to understand the concepts by doing investigations and identify and describe the applications of physics in the real world. Furthermore, it could also motivate students’ learning within both the affective and cognitive domains.

Moreover, the use of Tasks Inspired by Physics Education Research (TIPERs) have been investigated by other researchers (O’kuma et al., 2000; Maloney, O’kuma, Hieggelke, & Van Heuvelen, 2010; Hieggelke, Maloney, O’kuma, & Kanim, 2006) and have been successful in teaching concepts in physics courses. These TIPERs are focused on conceptual understanding and reasoning in different physics areas. In addition, TIPERs promote sense making and help students build a base with understanding (Hieggelke et al., 2006). Thus, it is fundamental to incorporate the TIPERs to provide students with not only conceptual understanding but also reinforce physics concepts.

Today, the predominant educational approach to high school physics relies on traditional lecture-based teaching that is sometimes ineffective and generates a perception that physics is only a collection of formulas (McDermott, 1993). Students already have a vague system of beliefs about the physical world, loosely based on their empirical experience, which is often wrong but deeply rooted in their way of thinking (Martin-Blas et al., 2010). Thus, conceptual understanding of physical concepts is very important for the success of students in STEM. This fact calls for an educational strategy that not only reflects the inherent structure but also considers the cognitive difficulties encountered by students. The likely increase in the use of computers and computer graphics in physics education and elsewhere calls for a new form of literacy (Torqvist et al., 1993). A new approach should be explored for students to relate, as well as apply, abstract knowledge learned in the classroom to concrete and complicated physical world.

Physics Survey Research

Based on the need for new approaches to high school physics instruction, the STEM team at Utah State

University conducted research to gather data from physics high school teachers in the United States. The purpose of the research was to investigate perceptions of physics teachers at high schools across the United States. The research included interview and survey data. The two national surveys were developed and disseminated based on the review of literature and preliminary interviews with selected high school Physics teachers in the Cache Valley area in northern Utah. Teacher interviews provided baseline data for the development of the surveys. Each survey consisted of multiple-choice questions and open-ended questions, and took 1015 minutes to complete. Data were collected for this research using the online survey technique. Online survey technique has been widely used in studies of online populations in the past decade because it provides access to large groups which would be “difficult to reach through other channels”, reduces the time required for survey implementation, and reduces interviewing costs (Dillman, 2007; Wright, 2005). The two surveys were posted on SurveyMonkey and distributed through email. Responses were recorded and collected through SurveyMonkey. The details of the survey questions will be discussed in the following sections.

The surveys used in this study consisted of three parts. Part one collected demographic information consisting of gender, educational level, job status, and teaching experiences. Part two addressed the perceptions of physics teachers regarding students’ physics learning in high school, difficult physics concepts to teach, and difficult physics concepts for students to learn. Part three dealt with learning and teaching methods in physics.

Survey Question Design

The interview and survey questions were evaluated by experts in physics, engineering education and education. The data for the research was collected in three stages described below.

Stage 1: Conduct interviews with local high school physics teachers. The objective of the interviews was to gain preliminary data on the difficulties in physics teaching and learning. The development of the interviews included reviewing literatures on physics education to ensure that the survey questions targeted the problems in physics teaching and learning. A questionnaire was created based on the literature review results and used during the interview. The questionnaire was presented and answered during different faceto face interviews with selected high school physics teachers in the Cache Valley area in northern Utah. The interview data provided a baseline for a national survey (Survey #1) as mentioned below.

Stage 2: Design Survey #1. The questions for a national survey were formulated based on the results of the face-to face interviews with teachers and research studies which indicate similar problems in Physics (Aubrecht

& Raduta, 2005; Saglam & Millar, 2006; Tornkvist et al., 1993). A total of 25 questions were included in Survey #1, consisting of 5 open-ended questions and 20 multiple-choice questions. Survey #1 collected information to address different questions on 1) background information on the teaching experience for different types of Physics classes, 2) the most difficult concept for teachers/students to teach/learn, 3) problems that teachers and students have in teaching and learning Physics, 4) types of physics classes (divided into General Physics and AP Physics), and 5) technologies that are being used for teaching and learning Physics.

Stage 3: Design Survey #2. Based on Survey #1 results, Survey #2 aimed at generating solutions to the problems/difficulties identified in Survey #1. Survey #2 included 20 questions in the following categories: solutions to specific identified problems in Survey #1, specific teaching strategies, educational policy, and comments on current available resources.

Participants

Three physics teachers from the Cache Valley area high schools were invited for the interview in Stage 1. They were all teachers with substantial experience in teaching high school physics (more than 8 years of teaching experience in physics).

For surveys #1 and #2, a sample of 1,000 high school physics teachers from 20 states in the United States was selected. The 20 states were selected because of their location, population, and diversity to make sure the sample from the twenty states represented the full spectrum of opinions of high school physics teachers in the U.S. The states were selected from four different regions according to the U.S. Census Bureau: Northeast (New York, Pennsylvania, Connecticut), Midwest (Ohio, Illinois, Michigan, Kansas, Wisconsin), South (Florida, Texas, Georgia, Maryland, North Carolina, Oklahoma), and West (Utah, California, Oregon, Arizona, Colorado, New Mexico). The names and emails of the 1,000 teachers (50 teachers per state) were obtained from the websites of the schools, which was available from the database of US High School Directory. From the selected 1,000 teachers, 24 email addresses were invalid which could have been due to transfer, retirement, or wrong information. Survey #1 was sent to a total of 976 teachers through email. After Survey #1 was closed, Survey #2 was sent to the same participants, including those no respondent participants in Survey #1, and except for the 42 who opted out of the study. Both Survey #1 and Survey #2 were resent to the no respondent emails four times with 37 daytime intervals to obtain a higher return rate.

Survey Analysis

Teachers' responses to all multiple-choice questions were downloaded from Survey Monkey, coded, and

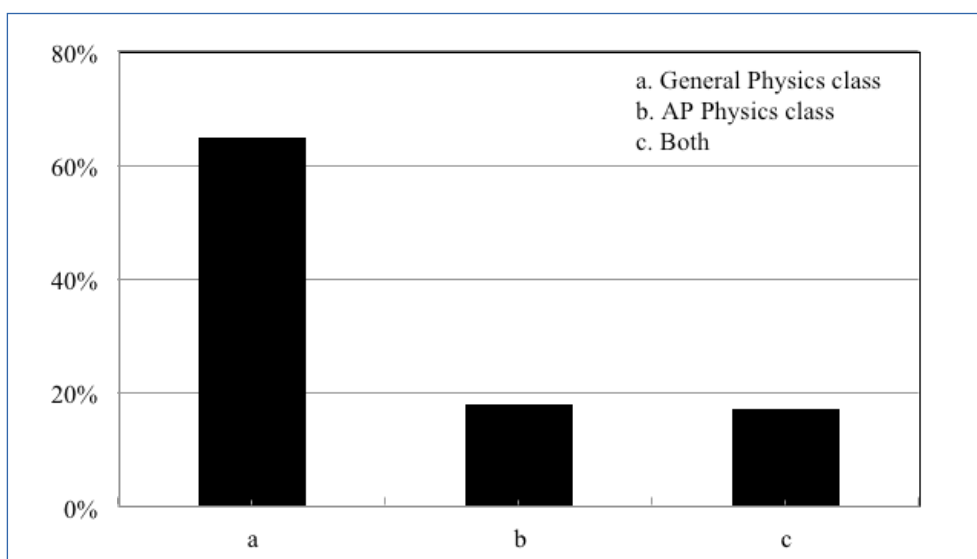


Figure 1. Types of Physics classes taught by teachers with 8 years of teaching experience.

analyzed twice by two assistants. The methodology described by Corbin & Strauss (2008) was used to determine the coding schemes of the answers to open-ended questions. For example, the data collected from the two open-ended questions: 1) *Do you think introducing interactive computer simulations in class will benefit the teaching and learning of physics? Why?* And 2) *Do you think there is something that could be done to help improve the teaching and learning of physics? Explain.* Two assistants categorized the data independently. After discussion, redundant categories were eliminated and a consensus was achieved between the two assistants on how to categorize the answers to each open-ended question. Then the two assistants coded the data twice separately and finally achieved an interrater agreement of 97% for the first question and 98.3% for the second question.

Results

Teacher Interviews

All three teachers that were interviewed for the preliminary survey had been teaching high school physics for grades 9-12 for more than 8 years. Also, they had experience teaching AP Physics and general physics. About 30 students were included in each of their physics class with Algebra I/II as the minimum math requirement. Two teachers had used various teaching methods in class to demonstrate concepts/topics in physics, including traditional lecture, video, physical models, hands-on practice/lab, and computer simulation. The third teacher did not use technology in the classroom. All three teachers used quizzes, lab activities, and AP test scores to assess students' understanding and their retention of knowledge in physics class.

The teachers agreed that the physics concepts, which were nonnutritive and hard to visualize, such as

electromagnetism, were difficult to teach. They also found students struggle with understanding fundamental concepts such as vectors, and applying the learned concepts to problems solving. The teachers indicated that math skills made a significant difference on academic performance. On average, students who had taken pre-calculus/calculus did better than the students with lower math skills (Algebra I/II).

Questionnaire Responses

Response rate on the questionnaire was calculated as the ratio of partial/completed survey to the total eligible sample, excluding outofscope cases (bounced email addresses). The total number of respondents for Survey #1 and Survey #2 was, 218 and 216 respectively, for response rates of 22.3% and 23.1%. According to Henderson (1990) and Denison & Mishra (1995), a response rate over 20% is adequate to conduct an exploratory test with data from a large number of samples.

Results of Survey #1

On average, 20% of the teachers participated in Survey #1 from each state. More than half of the teachers who filled the survey had more than 8 years of teaching experience. As shown in Figure 1, 81.7% teachers had experience in teaching general Physics classes, which emphasizes more on conceptual understanding. The data collected in the survey show that Physics is an optional class for high school students. Applying the concept learned to solve the problems and connecting mathematical concepts with Physics concepts were identified as two most difficult tasks for the students.

Figure 2 shows the most difficult concepts for teachers to teach and also for students to learn, according to the teachers' perception. Most teachers, regardless of teaching experience and class taught, experienced difficulty in

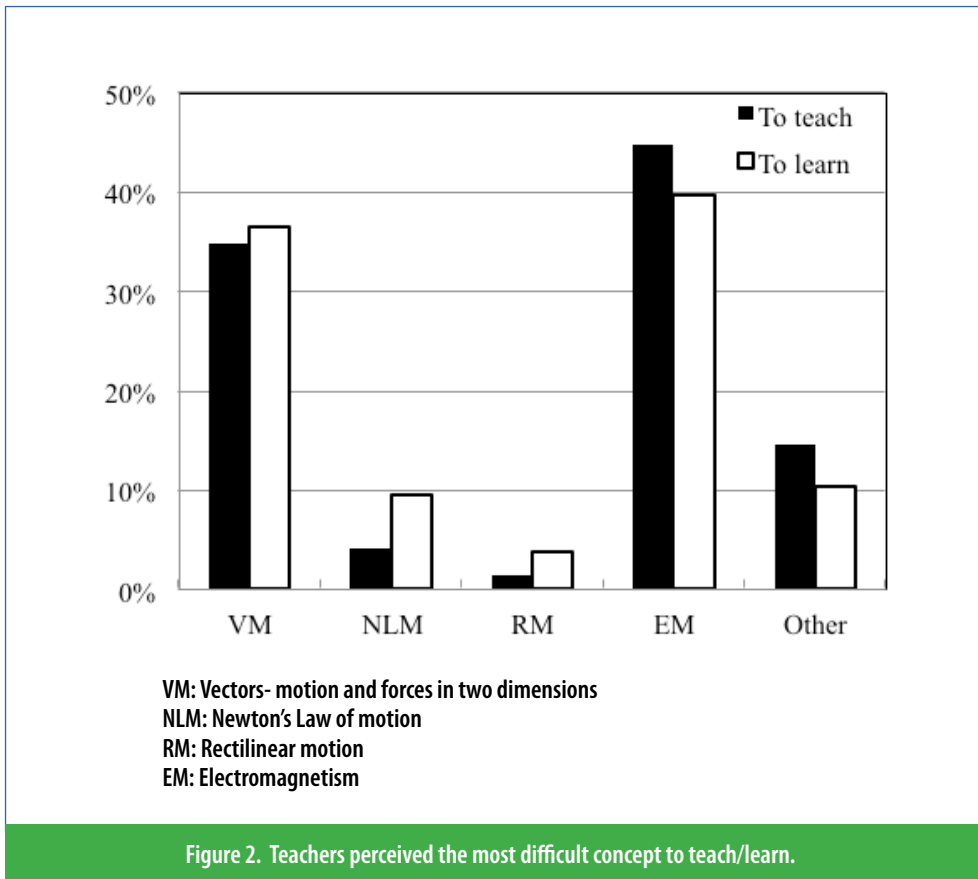


Figure 2. Teachers perceived the most difficult concept to teach/learn.

teaching abstract physics concepts defined in multiple dimensions. For example, electromagnetism and vectors motion and forces in two dimensions were identified as two most difficult concepts for both teaching and learning by more than 75% teachers. Concepts in modern physics, such as subatomic particles, were also suggested as difficulties in physics teaching and learning by some teachers. However, this study was focused on classical physics, which takes a larger proportion of high school physics. The

primary reason why vectors and electromagnetism were difficult concepts to teach was student spatial visualization ability. One teacher indicated that “students have a difficult time understanding that motion can be more than one direction at the same time.” Many teachers thought electromagnetism was even more difficult to teach and learn than vectors because of the lack of equipment and experience. Some of the comments included: “students are much less connected to the concepts of electrostatics

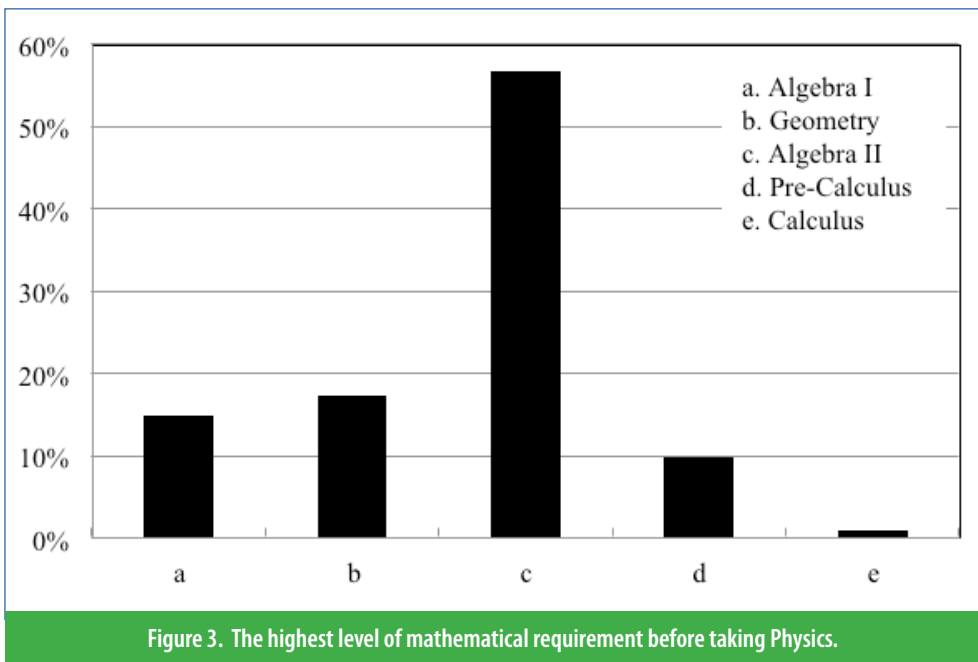


Figure 3. The highest level of mathematical requirement before taking Physics.

and magnetism than they are to any mechanics concepts,” “all they (the students) know (about EM) is that you flip a switch and things turn on but they cannot ‘see’ the charges or the fields,” and that “it is difficult for the kids to understand that there are external influences in the real world that we will not take into consideration when discussing general physics concepts.”

Regarding math skills, teachers indicated that most students are not prepared to undertake the mathematical problems involved in physics. Figure 3 shows the highest level of mathematics required from the majority of the students before taking the physics class. Algebra II was required in most general physics classes, however, many teachers agreed that math skills are a challenge for students. One teacher indicated that the “retention of math skills” is so low that “many (of the students) even have trouble with basic algebraic manipulation.” Another teacher mentioned that students “resist putting together the math and the physics concepts.”

Open-ended questions

Two open-ended questions about interactive computer simulations were asked in Survey #1. Teachers were asked to provide comments and suggestions about the use of computer simulations in the classroom and if they help improve the teaching and learning of Physics. The results showed that 90.4% of the teachers agreed on the benefits of introducing interactive computer simulations to the classroom and its importance on the teaching and learning of physics.

Table 1 and Table 2 show the coding schemes for the data collected from the two open-ended questions mentioned above. Nine categories were created for the question questions by the two assistants.

The majority of the respondents (88.5%) had a positive attitude toward the interactive computer simulations. Data from the teachers provided specific reasons why the interactive computer simulations would benefit physics teaching and learning. 24.8% of the teachers agreed that interactive computer simulations will benefit the teaching and learning of physics by visualizing the concepts: “Yes, because interactive computer simulations would help them visualize the physics concepts being taught.” Other teachers (9.5%) welcomed interactive computer simulations because they allow students to manipulate variables: Yes. . . It allows students to make very quick yet profound changes in the controlling variables associated with otherwise impossible to create (in terms of resources) system.

Moreover, many teachers (32.6%) would like to improve the teaching and learning of physics by introducing design activities during lab. Some teachers believe that understanding physics concepts should be emphasized. Some comments from the teachers included: “Give more practice with carefully designed

Code	Description of Code
Concepts	Computer simulations help students have a better understanding of concepts
Application	Computer simulations provide more opportunities for students to apply concepts
Visualization	Computer simulations help visualize concepts
Manipulation	Students can manipulate variables in computer simulations
Feedback	Computer simulations provide instant feedback to students
Affection	Students like computer activities
Neutral Attitude	Teacher or student has a neutral attitudes toward simulations
Negative Attitude	Teacher or student has a negative attitudes toward simulations
Other	Teacher mentioned that computer simulations would be beneficial, but didn't specify why

Table 1. Coding scheme and description of the open-ended question #1

Code	Description of Code
Lab	Use modeling instruction, design and labs
Class Size	Smaller class size
Pre-requisite	Improve students skills in pre-requisite courses
Equipment	More equipment and resources
Attitude	Change society's attitude on the importance of Physics in general
Teacher Qualification	More teacher training and development programs
Integration	Integration of disciplines with science
Concept	Emphasize concepts understanding
Other	Motivation, more time for in-class practice and make Physics a requirement

Table 2. Coding scheme and description of the open-ended question #2

and carefully selected items that will give them feedback with explanations computer based methods can be very useful," "Demystify tough concepts by teaching the simple foundation of the concept," and "I think if there was a database with teacher lesson plans, labs, project ideas, lecture notes, and other resources for all physics teachers to access that would be extremely helpful."

Results of Survey #2

To look more closely at the difficulties in the teaching and learning of physics, survey #2 was designed and distributed to the same group of teachers. Results of survey #2 showed that most teachers thought they need more time for in-class examples/practices, and promote students analyzing problems instead of relying on memo-

ization, 41.1% of teachers also suggested emphasizing conceptual understanding and 33.2% providing more inclass simulations and hands-on work. As well, most teachers pointed out that introducing three-dimensional interactive computer simulations with guidance for students are helpful for the teaching and learning of high school physics.

In addition, many teachers thought that electromagnetism was one of the most difficult concepts for students to learn/understand (44.8%). This result corresponds to two questions asked in the survey: (1) what is the most difficult physics concept to teach, and (2) what is the most difficult physics concept for students to understand and/or learn.

Teachers also indicated that "it is difficult [to teach

and learn electromagnetism] because the students can't see electricity/magnetism, unlike most of the other physics concepts," and that "[students] can understand some concepts but have trouble applying those concepts to a variety of problems." One instructor responded that "[field lines] are very abstract and difficult for students to apply, especially when the problem is three-dimensional." In addition, thirty-five percent (35%) of respondents responded favorably toward the use of some type of computer simulations in instruction to learn and visualize abstract physics concepts.

Teachers were in agreement with each other that difficult concepts in physics contribute to difficulty in learning and teaching. Further, the survey results indicated that there is a need for more effective instructional

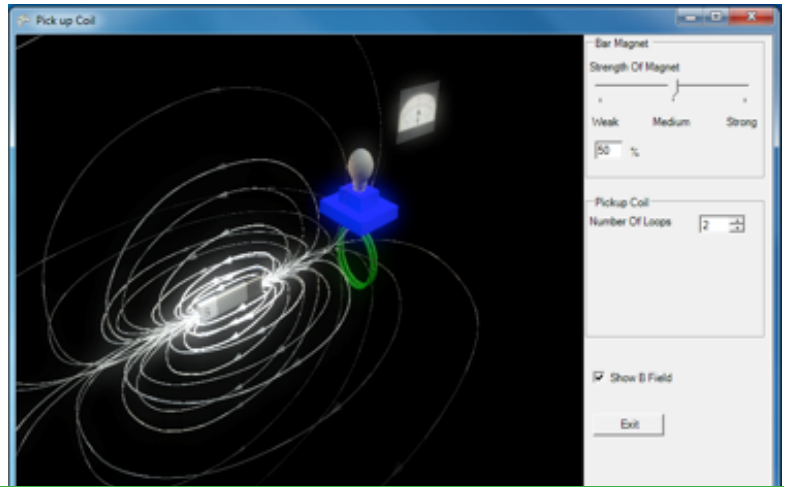
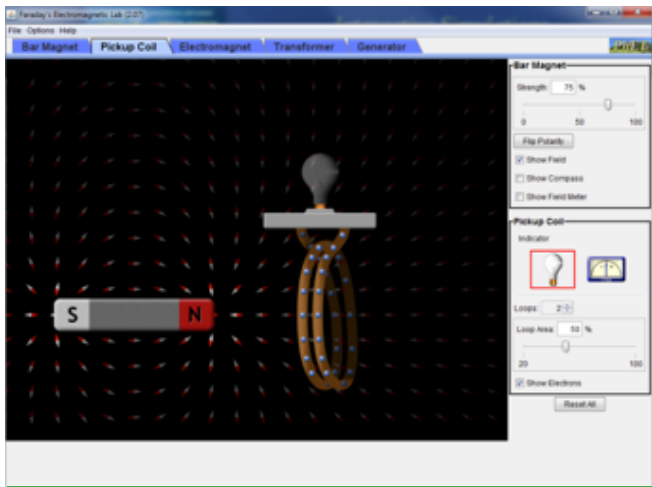


Figure 4. 3D simulation (left) and PhET simulation (right) used for the pilot study.

materials for high school physics and that 3D simulation could improve the learning of difficult concepts.

Pilot 3D Simulation Research

From the results of the national survey data, it was clear that 3D simulations could be a contributor to effective teaching and learning in physics. This led to pilot research conducted by the Utah State University research team to determine if 3D simulations showing different electromagnetism concepts focused on Faraday's Law was more effective than the PhET 2D simulations. The PhET simulations developed by the University of Colorado at Boulder (<http://phet.colorado.edu/>) are good tools that have been used by many physics teachers. However, these simulations are 2D in nature and lack the 3D visualization and self-guidance to effectively utilize. They are challenging for high school students to use by themselves as indicated by some teachers in the national surveys.

The pilot research consisted of 12 high school students who had already been exposed to the high school physics curriculum that included a section in electromagnetism. The students were assigned into three different groups: 1) 2D simulation only, 2) 3D simulation only (developed at USU), and 3) combination of 3D and 2D simulations. The 2D simulation used (Figure 4), also known as PhET simulation was mentioned as a teaching tool by different teachers in the national survey data.

The participants were asked to describe their overall understanding of Faraday's Law in the form of a drawing or a simple verbal explanation. Then, the participants were given 15 minutes to interact with the 3D simulation, a 2D simulation, or a combination of both, depending on the group they were assigned. After intervention with the simulations, students were asked to explain again their understanding of Faraday's Law, followed by a series of interview questions regarding different concepts on electromagnetism and Faraday's Law. In order to assess understanding of concepts, interview questions were

used to perform a cognitive evaluation during the activity. This verbal thought process was recorded and transcribed. The verbal transcripts were used to generate a list of common topics indicating different understandings or misinterpretations of the students.

The results obtained from this pilot research indicate that most students did not have a good understanding of 2D representations and they thought that field lines are constrained to a specific area. The 3D simulation helped to clarify the understanding of field lines and helped students with correcting the misunderstandings regarding field lines and magnetism. The following section discusses the results of the both research studies conducted by the USU team and recommends an alternative approach to physics learning and teaching.

Discussion and Alternative Instructional Approach to Improve Physics Teaching and Learning

The survey research provided the dimensions of crosscutting concepts and practices that should be addressed in high school physics. The survey results indicated that electromagnetism is seen as an important concept with broad significance across multiple sciences and for the success of students in high school and their preparedness. The survey also revealed the importance of relating interests and life experiences of students to different scientific or technical concepts, including those with high levels of depth and sophistication. Conceptual understanding of physical concepts is very important for the success of students in physics and STEM areas in general. Although there have been other research targeting difficult concepts in physics, the majority of these projects have been focused on classical mechanics (Dori & Belcher, 2005). However, with the current technological revolution an understanding of electromagnetism is necessary, especially to prepare students for science and engineering careers. In the context of engineering education, it is fundamental to study electromagnetism in order to learn

the process of engineering innovation and everyday applications (Taflove, 2002). Projects involving difficult concepts in electromagnetism have devoted much time to visualization of abstract phenomena. Such visualizations allow students to gain insight into the way in which fields transmit forces by watching how the motions of objects evolve in time and in response to those forces. This makes electromagnetism phenomena more concrete and more comprehensible (Dori & Belcher, 2005).

The PhET simulations and TIPERs have been contributing to the teaching and learning of high school physics by emphasizing students' understanding of physics concepts (Hieggelke et al., 2006). However, the impact of PhET simulations was limited because of the 2D design and the missing of guidance. As indicated by some teachers in the national surveys, comprehensive manipulation of simulations and 3D visualization are two main challenges in PhET for many high school students. It is proposed to incorporate the TIPERs in physics classroom along with 3D simulations to prepare students with spatial visualization skills that are vital to the success in STEM disciplines.

As was presented in the results of the research, 3D interactive computers simulations can help the teaching and learning of abstract concepts in high school physics. 3D computer simulations concretize abstract concepts and connect mathematics and physics principles. For example, field lines are neither visible nor even an object that actually exists in physical world. It is a concept created to help describe the distribution and strength of magnetic field (Figure 5). Although the field lines are described as 3D in physics textbooks, the figures shown in textbooks are all 2D. It is a big challenge for high school students to convert the 2D figures into 3D visualizations (Osborn & Agogino, 1992; Veurink et al., 2009). In the 3D space created in the computer simulations, the students would be able to see the distribution, direction and density of field lines, how the field lines are intersected by close conductive loops, and the change of field lines within the close loops while the magnet or the loops are moving in different directions.

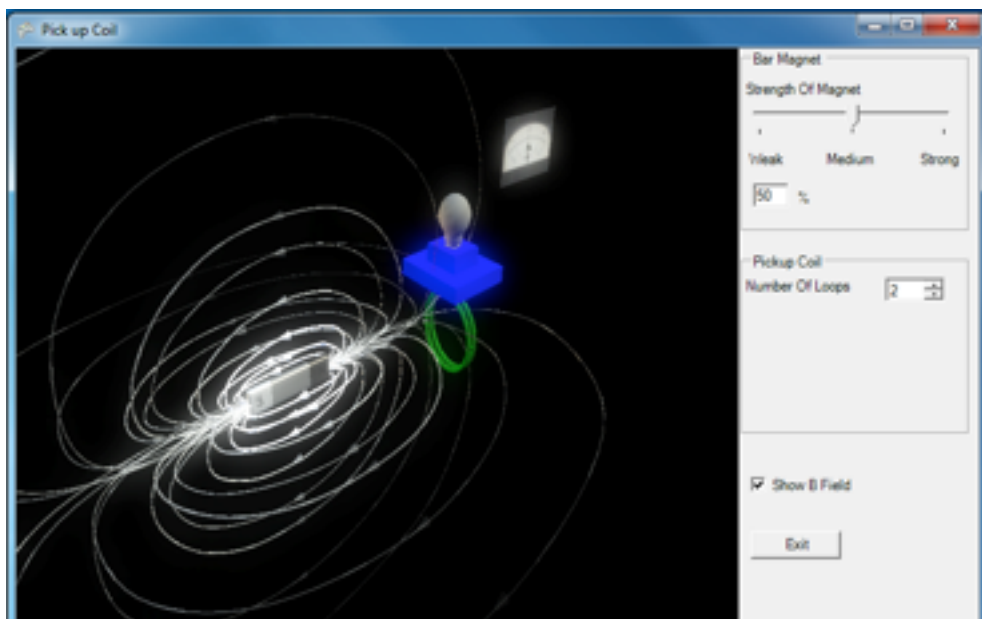


Figure 5. 3D interactive simulations to improve understanding of concepts.

3D interactive computer simulations also allow students to manipulate the computer simulations by themselves. Students would be able to explore all possibilities of one principle under various situations. For example, guided by the simulations, the students could test the impact of number of loops, strength of magnet and the speed of movement of the magnet/loops in various directions on the strength of induced current. This can simultaneously demonstrate mathematical equations of the parameters while, showing graphically what is happening with the loop and coil (Figure 5). It can not only help improve students' mathematics skills but also show physical meanings of the mathematical equations as well as provide instant feedback to the students.

Alternative Instructional Approach

For students to apply the abstract knowledge they learn in the physics classroom to the concrete and complicated physical world, new instructional approaches are needed for high school physics. Research results like these provide a framework for establishing an approach to building tools to aid in student learning. A mix of existing methods strategically used to complement one another could produce more effective teaching and learning of difficult concepts in physics.

An alternative instructional approach that combines engineering design activities, modified PhET's and physics TIPERs could provide the learning experiences that allow students to become familiar with real world applications. TIPERs are focused on conceptual understanding and reasoning in different physics areas. In this case, TIPERs would be used not only for conceptual understanding but also to reinforce electromagnetism concepts or other difficult physics concepts. There are many ways in which these TIPERs

can be adapted and modified according to the specific needs of the lesson. Thus, it is fundamental to incorporate the TIPERs to the instructional model in order to provide students with a base that would allow students to work on the engineering design activity (EDA). The EDA is a complex system, not easily defined, and students need an understanding of non-linear and unbounded constructs, which could be possible through the use of TIPERs.

The instructional approach could promote physics learning through scientific inquiry, integrating an engineering design activity to expand students' exploratory learning. The ultimate goal is to create an empowering learning environment that integrates engineering design to the high school physics curriculum in order to help students learn difficult concepts. Curriculum development regarding the integration of physics in the interactive 3D simulations would include EDA's the physics content and TIPERs. Instruction could be based on Faraday's Law and engineering systems thinking (Figure 6). The components of this system could be used as the foundation to create all activities. The physics content would entail the design and development of physics lessons integrating EDA.

Thus, it is fundamental to incorporate the TIPERs to the EDA in order to provide students with a complete engineering systems thinking base that would allow students to work on the EDA. TIPERs would be used not only for conceptual understanding but also to reinforce concepts. Figure 7 shows how the TIPERs could be integrated to the curriculum.

The results of this research and related literature suggest a strategy integrating engineering design activities

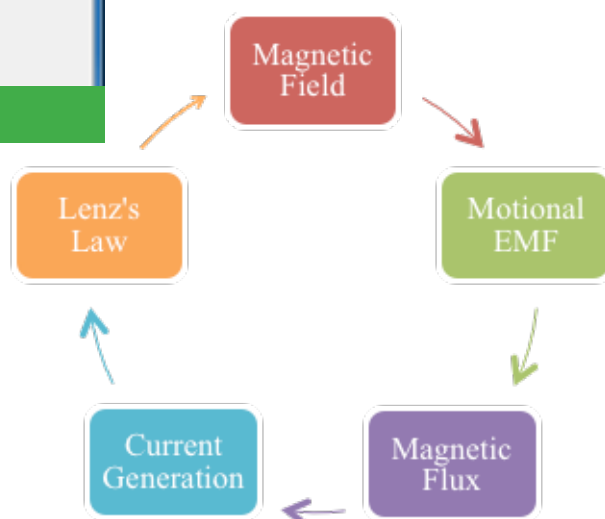
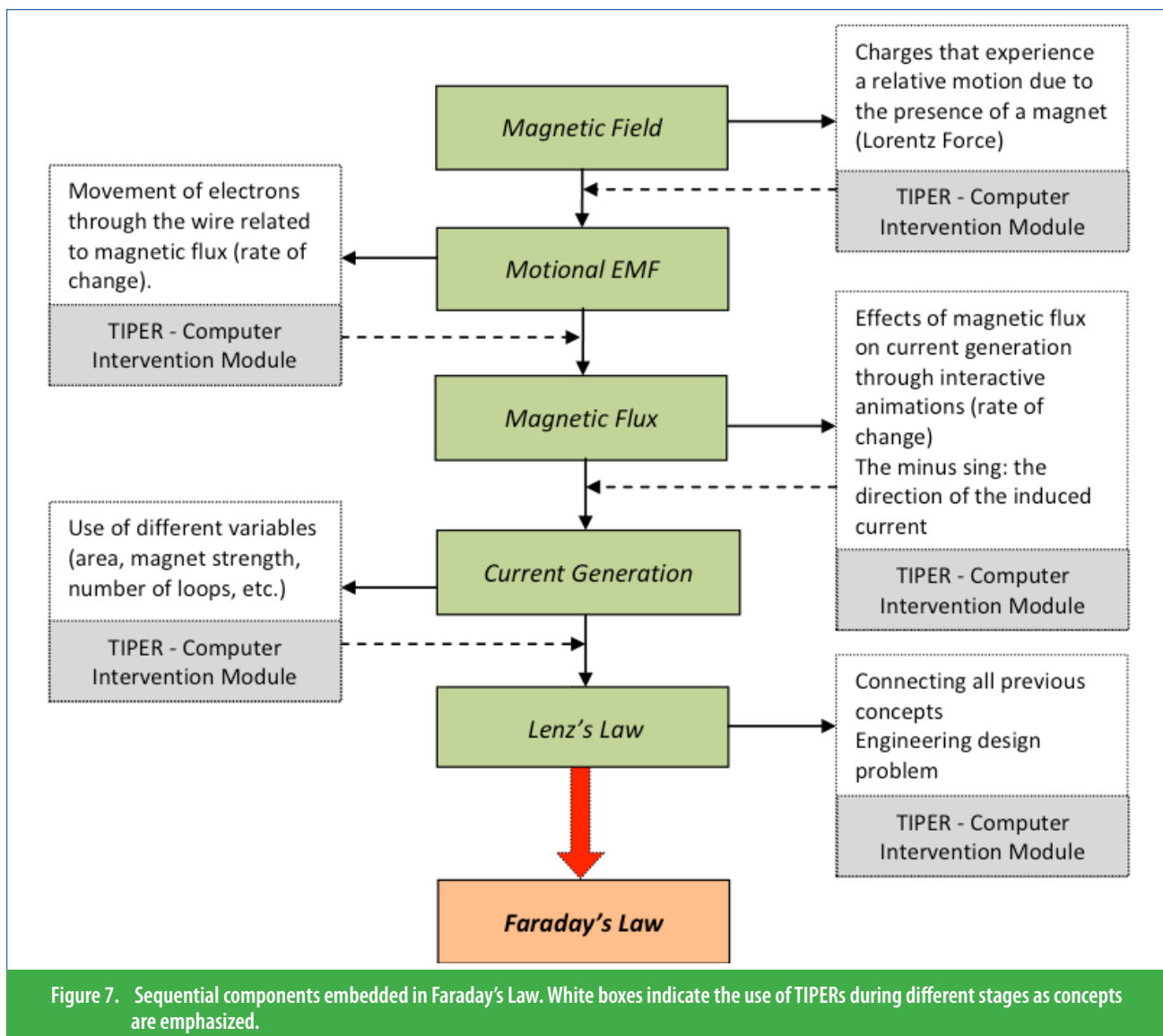


Figure 6. Engineering Design System Thinking based on all components embedded in Faraday's Law.

in high school physics instruction. This strategy could improve the science readiness of high school students in the U.S. as well as promote the NGSS initiatives to learn science through engineering design processes, and improve and promote the learning and teaching of difficult physics concepts in high schools. Using alternative approaches to physics learning and teaching could promote interest and understanding in physics.

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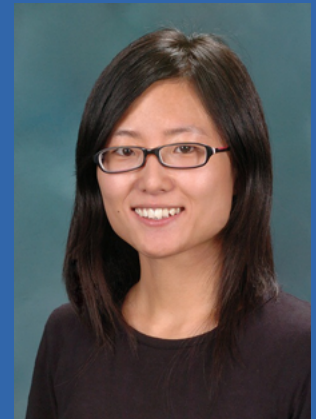
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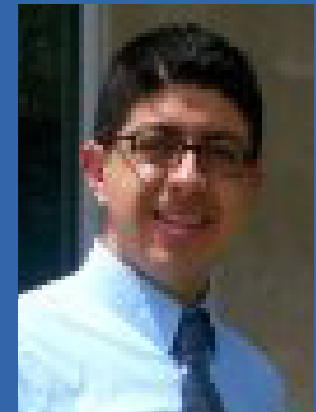
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