Modeling Instruction in AP Physics C: Mechanics and Electricity and Magnetism

by

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ABSTRACT

Modeling Instruction is a constructivist, student-centered approach to teaching science, where students perform experiments to collect data and create models—linguistic, mathematical, graphical, and diagrammatic—that represent the data. Students then test their models with more experiments and other methods, refining their models for use in various situations. Many studies have indicated that Modeling Instruction promotes student achievement in science, but no studies have connected Modeling Instruction with AP Physics C: Mechanics and Electricity and Magnetism. This action research study (a) clarifies the cognitive theory underlying Modeling Instruction and connects this theory to general learning principles, (b) updates current Modeling Instruction models explicitly to include properties, calculus-based mathematical representations, other representations, rules of behavior, and sequence of activities and information, and (c) creates new models for topics outside the standard Modeling Instruction materials with properties, representations, rules of behavior, and sequence of activities. Data from baseline information, 2017 AP Physics C exams, 2015 AP Physics C practice exams, Force Concept Inventory, Mechanics Baseline Test, and Brief Electricity and Magnetism Assessment are used to determine the efficacy of Modeling Instruction. Results from this study will add to the research base for Modeling Instruction and AP Physics C, and provide information regarding future studies.

Keywords: Modeling Instruction, AP Physics C, action research

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LIST OF ABBREVIATIONS

AMTA .... American Modeling Teachers Association

AP .... Advanced Placement

BEMA .... Brief Electricity and Magnetism Assessment

DEOC .... District End-of-Course

E&M .... Electricity and Magnetism

FCI .... Force Concept Inventory

MBT .... Mechanics Baseline Test

MSP .... Mathematics and Science Partnerships

NGSS .... Next Generation Science Standards

NSF .... National Science Foundation

PER .... Physics Education Research

PSSC .... Physical Science Study Committee

SCIS .... Science Curriculum Improvement Study

STEM .... Science, technology, engineering, and mathematics

US DoE .... United States Department of Education

CHAPTER 1 – RESEARCH OVERVIEW

Science, technology, engineering, and mathematics: Together, these fields in education are combined into the acronym "STEM," which has become one of the most ubiquitous terms in education. A quick search of the term "STEM Education" returns "about 32,600,000 results" from the web tab and "about 9,750,000 results" from the news tab of Google (STEM Education, n.d.), and many of the results from the news tab reference articles describing multimillion dollar donations to many different organizations. From the sheer number and scope of these references, many groups have a vested interest in the quantity and quality of students who pursue careers in STEM fields. Further, due to the profound impact teachers have on students, these organizations have become greatly interested in teacher quality; for STEM education, the United States Department of Education (US DoE) contributed 141.9 million dollars in 2013, 149.7 million dollars in 2014, and requested 319.7 million dollars for 2015 (US DoE, 2014).

Many universities have received funds for research through the US DoE or NSF, and one option for those in the STEM fields to obtain resources is through the Mathematics and Science Partnership (MSP) Program. This "program is intended to increase the academic achievement of students in mathematics and science by enhancing the content knowledge and teaching skills of classroom teachers" (US DoE, n.d.). From 1989 to 2005, professors at Arizona State University received MSP funds to develop high school science materials for Modeling Instruction, a method of teaching science that "emphasizes active student construction of conceptual and mathematical models in an interactive learning community" (Jackson, Dukerich, & Hestenes, 2008). The Modeling Instruction Program was recognized in 2001 by a US DoE Expert Panel in Science "as one of only two exemplary K-12 science programs out of 27 programs evaluated" (Jackson, Dukerich, & Hestenes, 2008). Though the MSP grant was discontinued in 2005, Modeling Instruction is administered through a professional organization known as the American Modeling Teachers Association (AMTA). The mission of the AMTA "is to provide professional development for science teachers in the Modeling Method of Instruction, provide resources that support the use of Modeling Instruction in physics, chemistry, biology and middle school science classrooms, [and] to support and enable collaboration among Modelers" (AMTA, 2016).

Advanced Placement (AP) Physics C: Mechanics and Electricity and Magnetism are each "equivalent to a one-semester, calculus-based, college-level physics course[s]. [The courses are] especially appropriate for students planning to specialize or major in physical science or engineering. … Introductory differential and integral calculus is used throughout the course[s]" (College Board, 2016). Students are expected to do the following by the end of any AP secondary science course or set of courses:

1. Read, understand, and interpret physical information—verbal, mathematical, and graphical.
2. Describe and explain the sequence of steps in analysis of a particular physical phenomenon; that is,
    a. describe the idealized model to be used in the analysis, including simplifying assumptions where necessary;

b. state the concepts or definitions that are applicable;
c. specify relevant limitations on applications of these principles;
d. carry out and describe the steps of analysis, verbally, mathematically, or graphically; and
e. interpret results and conclusions, including discussion of particular cases of special interest.

3. Use basic mathematical reasoning—arithmetic, algebraic, geometric, trigonometric, or calculus, where appropriate—in a physical situation or problem.
4. Perform experiments and interpret the results of observations, including making an assessment of experimental uncertainties. (College Board, 2014)

The goals described by the College Board are related to the goals of Modeling Instruction because students who complete a course with Modeling Instruction understand how to use multiple representations—linguistic, mathematical, diagrammatic, and graphical—for physical phenomena and build models for a range of situations. This dissertation will describe the implementation and discuss the effectiveness of Modeling Instruction in AP Physics C: Mechanics and Electricity and Magnetism during 2016-2017.

Problem of Practice

The problem of practice for this dissertation is inadequate student achievement in AP Physics C: Mechanics and Electricity and Magnetism, and the proposed solution is to incorporate Modeling Instruction theory and practice in the researcher's courses during the 2016-2017 school year. Both AP Physics C courses were offered at the researcher's high school for the first time in 2015-2016, and the high school is one of two schools in the district that offers Mechanics and the only school that offers Electricity and Magnetism. Therefore, no materials were given to the researcher by the district; information had to be collected from the College Board website, AP Physics teacher community, and other AP Physics teaching sources. In addition to AP Physics during 2015-2016, the researcher taught Honors Physics using Modeling Instruction. As the researcher investigated curriculum organization, instructional methods, and assessments for AP Physics, the researcher realized that the ideas embedded within Modeling Instruction would be appropriate for AP Physics C and have the potential to impact positively student achievement on the AP exams and within science courses that the students will take in their collegiate careers. However, after a brief search for relevant literature, the researcher realized that there was no information connecting the content of AP Physics C with the methods of Modeling Instruction. Therefore, the researcher will (a) utilize the cognitive theory behind Modeling Instruction to modify previous models or create new models for AP Physics C content, and (b) implement Modeling Instruction methods during AP Physics C: Mechanics and Electricity and Magnetism in 2016-2017.

Research Question and Purpose of Action Research

Because the effect of Modeling Instruction methods and theory on the student achievement in AP Physics C: Mechanics and Electricity and Magnetism is unknown, the research question for this dissertation will be the following: What is the effect of Modeling Instruction on the achievement of students in AP Physics C: Mechanics and Electricity and Magnetism? This question is unique within literature pertaining to

Modeling Instruction and AP Physics C, and this dissertation will contribute to the theoretical and experimental research in physics education research (PER).

The purpose of the present Action Research study is to determine the efficacy of Modeling Instruction in AP Physics C for twenty students in a suburban high school in South Carolina. The specific purpose of the study is to (a) clarify the cognitive theory underlying Modeling Instruction and connect this theory to general learning principles, (b) update current Modeling Instruction models to explicitly include properties, calculus-based mathematical representations, other representations, rules of behavior, and sequence of activities and information, and (c) create new models for topics outside the standard Modeling Instruction materials with properties, representations, rules of behavior, and sequence of activities. The general purpose is to contribute to the knowledge base within PER for the topics of Modeling Instruction and AP Physics C.

Action Research Design and Methodology

To determine the extent student achievement is impacted by the interventions, curricula, and instructional methods, organizations utilize research to answer questions about their programs and provide evidence about the efficacy of the programs. Research may happen on the national, state, district, school, or teacher levels, and have a scope from thousands of teachers and students to a single teacher and students in one class. Historically, "research has been conducted primarily by professionals whose principal education included training in the conduct of research studies," but "more and more research is being conducted by *practitioners*--people whose primary education and training is *not* in research methodology" (Mertler, 2014). A specific "type of practitioner-based research, known as *action research*," can be

> defined as any systematic inquiry conducted by teachers, administrators, counselors, or others with a vested interest in the teaching and learning process. … The basic process of conducting action research consists of four steps:
>
> 1. Identifying an area of focus
> 2. Collecting data
> 3. Analyzing and interpreting data
> 4. Developing a plan of action (Mills, 2011; Mertler, 2014)

Once the plan of action has been implemented, the teacher-researcher will "make revisions and improvements to the project for future implementation, … [and] the effectiveness of the revisions would be monitored and evaluated, with new improvements developed for the next phase of implementation" (Mertler, 2014). The cyclical nature of action research gives power to the teacher-researcher, because they may build from previous research experience to make major changes and improvements for a particular course, department, or issue in a school. This study will utilize action research to develop robust AP Physics C: Mechanics and Electricity and Magnetism courses for the benefit of the researcher and others who teach AP Physics C.

Students for this study will be selected by enrolling in the researcher's AP Physics C: Mechanics and Electricity and Magnetism courses during 2016-2017. There will be twenty students in this study, and students will have the option to opt out of the study.

The site for this study will be a large, suburban high school in the southeastern part of the United States. The high school has a student body of over 4,000 students, and the ethnic composition is 82% Caucasian, 12% African-American, 3% Hispanic, and 3% other ethnicities. Approximately 37% are served by gifted and talented program, and 6% are classified as students with disabilities. The high school has received an absolute rating of "Excellent" from the state Department of Education from 2010 to 2014, and offers over 250 courses. The school's clubs and teams achieve a high level of success, driven by dedicated and talented students, teachers, and coaches.

This study utilizes two different quantitative Action Research designs: A one-group pretest-posttest method and a one-shot case study (Mertler, 2014). A quantitative design is appropriate to answer the Problem of Practice because this study seeks to understand the extent to which Modeling Instruction affects student achievement in AP Physics C. For the one-group pretest-posttest method, student information will be collected on the:

- 2015 AP Physics C: Mechanics practice exam
- Force Concept Inventory (FCI)
- Mechanics Baseline Test (MBT)
- 2015 AP Physics C: Electricity and Magnetism practice exam
- Brief Electricity and Magnetism Assessment (BEMA)

In the one-shot case study, student final numerical grades for AP Physics C: Mechanics and Electricity and Magnetism and scores from the 2017 AP Physics C: Mechanics and Electricity and Magnetism exams will be collected. Additionally, baseline information is collected from students:

- Final numerical grade from the highest mathematics and science courses taken by the student.
- DEOC or AP scores from the highest mathematics and science courses taken by the student.

Simple statistical analysis—mean, median, standard deviation, range—will be performed on the AP exams, FCI, MBT, and BEMA, and correlations are made between scores on these assessment and baseline information from previous courses.

Research findings will be discussed after completion of the data analysis.

Historical Context

As the number of students entering secondary schools greatly increased between 1890 and 1900, the educational programs within these schools needed organization. Science was included in the course of study, and the expectation was that all students were to take science courses that had both content and laboratory parts (Bybee, 2010). However, standardization of curriculum, instruction, and assessment became the predominant methodology when operating schools between 1900 and 1950, and—in most cases—science became a list of vocabulary words to be memorized and regurgitated (Spring, 2014). After the launch of *Sputnik I* by the Soviet Union, science education gained a higher priority with the government of the United States and received an influx of funds to create curriculum and instruction that would develop the next generation of American scientists and engineers. One influential group, the Physical Science Study Committee (PSSC), produced curriculum and instruction that emphasized scientific thinking—multiple representations, developing models, and the unity of science—within the context of specific science content (Haber-Schaim, 2006). The ideas developed by the PSSC have permeated science instruction in the last 60 years, and these ideas continue to be developed within inquiry-based, modeling, and other types of curriculum and instruction.

With the widespread adoption of the Next Generation Science Standards (NGSS) and other new sets of similar science standards—including South Carolina in 2014—science education in the United States has reached a unique point in its history. The NGSS feature "three distinct and equally important dimensions to learning science" (NGSS Lead States, 2013), and the dimensions are crosscutting concepts, science and engineering practices, and disciplinary core ideas. "These dimensions are combined to form each standard—or performance expectation—and each dimension works with the other two to help students build a cohesive understanding of science over time" (NGSS Lead States, 2013). The NGSS are an extension of the inquiry-based ideas from the PSSC and other educational and learning theorists because all students are expected to use scientific and engineering practices within the context of specific science content. This curricular organization and set of instructional practices allows students to develop their own understanding of the science content and relationships between the aspects of the science content, in addition to increasing their problem-solving skills, creativity, and cooperation with other classmates.

Conceptual Framework

The theory of learning that provides underlying ideas for Modeling Instruction is known as constructivism. "Constructivism's central idea is that human knowledge is *constructed*, that learners build new knowledge upon the foundation of previous learning" (Kanselaar, 2002). This theory is not a single idea; rather it encompasses the following features:

- a set of epistemological beliefs (that is, beliefs about the nature of reality, whether there is an independent reality – c.f. von Glasersfeld (2001) or Bereiter (in press);
- a set of psychological beliefs about learning and cognition (e.g. that learning involves constructing one's own knowledge);
- a set of educational beliefs about pedagogy, the best way to support learning (e.g. that one should allow the learner to define their own learning objectives; that knowledge emerges from constructive interaction between the teacher and the student or between collaborating students). (Kanselaar, 2002)

The two major historical strands are cognitive constructivism, developed by Jean Piaget in the early to mid-20th century, and social-cultural constructivism, developed by Lev Vygotsky in the early 20th century. "Although they share some common ideas, there exist significant differences between them. On the topic of stages of development, Piaget believed that development precedes learning, while Vygotsky believed the opposite" (Kanselaar, 2002). Modeling Instruction is unconcerned with this difference, and focuses more attention on psychological ideas about learning and cognition and educational ideas about pedagogy.

The theoretical base of Modeling Instruction is grounded in constructivism, but focuses on the idea of a model as its thematic core. A model is "a *representation of* ***structure*** in a material system, which may be real or imaginary" (Hestenes, 2006), and models exist in many different ways. Humans have individual mental models of the manner in which a given physical or imaginary system works—for example, the water cycle—and groups have established common conceptual models about a system. Individual mental models and group conceptual models are open for revision if new information about the physical world is presented through the collection of data; in this case, the existing model is either modified to accommodate the new data or a new model is created that better explains the system.

The modeling cycle brings the idea of a model to the classroom because information is presented in the following manner:

1. Model development: Students are presented a physical situation—for example, a cart rolling on a track—and they must determine the properties of the situation that may be measured or calculated. Students then perform an experiment with the equipment and develop an individual mental model and group conceptual model about the physical situation.
2. Model deployment: Students create representations—linguistic, mathematical, graphical, and diagrammatic—to describe further the model, and perform further work to determine the limits and applicability of the model.

After developing and deploying the model, students formally create connections between the properties, representations, and rules of behavior for their individual mental model and group conceptual model. The role of the educator is to lead the students to a conceptual model that is similar to the model established by the general scientific community, and the educator does this by creating a systematic sequence of learning experiences (see Appendices A and B for information about models in AP Physics C).

Dissertation Overview

This dissertation has four more chapters discussing previous literature, methodology, research findings, and a summary and discussion. Chapter 2 is the literature review, which will provide an overview of studies related to Modeling Instruction. These works will provide a historical context for this research, theoretical foundations of constructivism and Modeling Instruction, information on measurement instruments, and results of previous Modeling Instruction studies. Information will also be presented regarding the impact of Modeling Instruction on students from diverse backgrounds. Chapter 3 will discuss the methodology for the research question, positionality of the researcher, and data collection and analysis. Chapter 4 will present the data for each research question and discuss any problems that occurred during the collection process. Chapter 5 will provide a summary and discussion of the data from chapter 4, including limitations of the study, interpretation of results, and implications of the results. Chapter 5 will also critically examine the data to determine whether Modeling Instruction had an effect on student achievement in AP Physics C and provide ideas for future research.

Conclusion

The problem of practice for this dissertation is inadequate student achievement in AP Physics C: Mechanics and Electricity and Magnetism. This study will utilize quantitative action research in the form of a one-group pretest-posttest and one-shot case study to evaluate the proposed solution. Students will take several assessments in mechanics and electricity and magnetism, and scores on these assessments and the AP Physics C: Mechanics and Electricity and Magnetism exams are used to understand any impact of Modeling Instruction on student achievement. Constructivist theory provides the foundation for modeling theory, and these theories provide ideas about the manner in which science should be taught. Modeling Instruction has been created to align curriculum, instruction, and assessment with modeling theory, providing a way to address student misconceptions and create accurate learning for each student.

CHAPTER 2 – REVIEW OF THE LITERATURE

Science classes have been an element in the course of study throughout the history of education in the United States, though mathematics and science classes gained special prominence after the launch of *Sputnik I* by the Soviet Union in 1957. Concerned that the United States was lagging behind the Soviet Union in scientific and technological research, the federal government began to pour large amounts of money into science education. One organization to receive funds from the National Science Foundation (NSF) was the Physical Science Study Committee (PSSC), and this group was led by Massachusetts Institute of Technology's (MIT) Jerrold Zacharias and Francis Friedman (MIT Libraries, 2012). Ideas and materials from the PSSC were well-developed, and many have become embedded in modern concepts of science education. A modern method—with roots in the ideas developed by the PSSC and Robert Karplus—in science education is Modeling Instruction, a hands-on, student-centered approach to teaching both the process and content of scientific disciplines. Modeling Instruction utilizes laboratory experiences to engage students in the science content to create a conceptual model, then students test and refine the conceptual model to determine its application and limits. This instructional technique and underlying pedagogy have been developed for physics, chemistry, biology, and physical science courses.

The problem of practice for this dissertation is inadequate student achievement in AP Physics C: Mechanics and Electricity and Magnetism, and this literature review will discuss the problem of practice in the context of learning theory, modeling theory, and previous results of Modeling Instruction studies. The learning theory section will discuss constructivism, the modeling theory section will discuss work by Hestenes, and the previous results section will discuss Modeling Instruction studies that are relevant to this dissertation. In addition, a section of the literature review will discuss studies related to the impact of Modeling Instruction on learners from diverse backgrounds. There are several studies related to Modeling Instruction in high school physics and introductory college physics courses, but there are no available studies discussing the effect Modeling Instruction has on student achievement in AP Physics C: Mechanics and Electricity and Magnetism. This dissertation research will generate new information for the research base in Modeling Instruction and AP Physics C by clarifying underlying theory, creating new models, and providing results with the assessment instruments.

Historical Context

Prior to the mid-1800s, science and science education in the United States did not exist in a structured manner. However, "the public's interest in science and the scientific method increased in the late 19th century" (Bybee, 2010), partially due to scientific progress and technological advances associated with the industrial revolution. In addition, high school attendance increased drastically between 1890 and 1900, with enrollment more than doubling during this decade. In 1892, "the National Education Association formed the Committee of Ten on Secondary School Studies under the leadership of Harvard's president, Charles Eliot" (Spring, 2014). The final report from the Committee of Ten "established a general framework for discussion of the goals of secondary education" (Spring, 2014), and science education was included in the framework. "The report underscored the importance of science for all students, whether they intended to go to college or enter the workforce" (Bybee, 2010), and made explicit the need for laboratory work in a high school science curriculum. To specify which type of scientific experiments were expected from secondary students, Eliot "asked the physics department at Harvard to develop an entrance requirement that emphasized the laboratory as part of high school physics courses" (Bybee, 2010). In 1889, these laboratories were compiled into a list and published as the *Harvard University Descriptive List of Elementary Physical Experiments*. The "list became the basis for a physics course and later for a national course in physics, ... [and] widespread acceptance of this report became the de facto first voluntary national standards for science" (Bybee, 2010).

The era between 1900 and the end of World War II may be considered a time of scientific management in the American school system. In scientific management, "standardization became the magic word. [District and school] administrators were preoccupied with standardizing student forms, evaluations of teachers and students, attendance records, and hiring procedures" (Spring, 2014). During this quest for standardization, administrators became obsessed with cost-effectiveness; taking a cue from the business world, administrators began to approach every program with cost-benefit analysis. As a result of standardization, science—along with many other disciplines—became a set of facts to be memorized rather than experiences to be understood. This sterilization eliminated the process of science, and produced students who are unaware of the foundational meaning of the "facts." John Dewey, widely known for his progressive ideas about education, discussed the role of scientific process in an address at a meeting for the American Association for the Advancement of Science. Dewey (1910) argued that science "has been taught too much as an accumulation of ready-made material with which students are to be made familiar, not enough as a method of thinking, an attitude of mind, after a pattern of which mental habits are to be transformed." Further in the discussion, Dewey states that "surely if there is any knowledge which is of most worth it is knowledge of the ways by which anything is entitled to be called knowledge instead of being mere opinion or guess work or dogma" (Dewey, 1910). This sentiment of helping students understand the ways by which anything may be taken as "knowledge" was counter to standardization because it required experimentation and use of the scientific process. Laboratory work is often messy, intellectually and materially, whereas standardization strives for perfectly predictable results. In an ironic twist, Dewey's ideas about the scientific process as a method of inquiry about a topic were taken by those seeking standardization and changed into a rigid structure called the scientific method. "Soon the scientific method was included in textbooks, thus becoming part of the knowledge that students had to memorize" (Bybee, 2010). Even today, more than 100 years after Dewey's ideas, some textbooks begin with the scientific method and incorrectly tout this formal structure as the only way to perform the scientific process.

"After World War II, global events, particularly the Cold War between the United States and the Soviet Union, directly affected American schools" (Spring, 2014). Science education was greatly impacted because many were concerned the United States was falling behind the Soviet Union in engineering and technological advances. "The

National Science Foundation (NSF) was established [in 1950] both to attract more students to science and engineering courses and to fund basic research" (Spring, 2014). One leader in the establishment of the NSF, Vannevar Bush, "believed that improvement of science teaching in high schools was imperative if latent talent was to be properly developed. He viewed as a great danger the prospect of high school science teachers failing to awaken interest or provide adequate instruction" (Spring, 2014). Although legislators United States Senate and House of Representatives were slow to provide federal funding to schools during the 1950s, their sentiments changed dramatically when the Soviet Union launched *Sputnik I*. In response, Congress passed the National Defense Education Act (NDEA), "which appropriate[s] $70 million for each of the next four fiscal years to be used for equipment and materials and for the expansion and improvement of supervisory services in the public schools in science [and] mathematics" (Spring, 2014). One aspect of this funding was the creation of new curricula, and "money flowing from the NSF was used to develop curriculum materials and to train teachers" (Spring, 2014).

The Physical Science Study Committee (PSSC) was formed by Jerrold Zacharias, a physicist at MIT and member of the United States Office of Defense Mobilization's Science Advisory Committee. "At the urging of his colleagues on the Science Advisory Committee and officials at the National Science Foundation in July of 1956, Zacharias began to assemble the key players" (Rudolph, 2006). These individuals were scientists—primarily physicists—from major research universities and other important figures in education and technology, such as "MIT president James Killian, Polaroid founder Edwin Land, and Educational Testing Service president Henry Chauncey" (Rudolph, 2006). By the time *Sputnik I* was launched by the Soviet Union, work by the PSSC was well underway and on track to begin implementation in high school physics within five years. However, the "launch shocked the nation and brought even greater pressure for reform in all science subjects along the path set by PSSC" (Rudolph, 2006), and funds from the NSF poured into the project. The first draft of the materials was completed by 1958, and a full course was ready for high school science teachers by 1960.

Up to and during the 1950s, the vast majority of high school physics courses were delivered by textbooks. The most popular was *Modern Physics*, published by Holt, and "in the entire book there were no descriptions of experiments or graphs of results of experiments that would justify any of the book's many assertive statements" (Haber-Schaim, 2006). In addition, "there was no laboratory program to go with the textbook. ... For [students in these courses,] science was equated with vocabulary" (Haber-Schaim, 2006). Zacharias had a different perspective about the manner in which physics and chemistry should be taught, and his ideas led to a course that was unique. For Zacharias, "physics and chemistry [were to be presented] as a living discipline, not as a body of finished, codified facts to be memorized. In today's language, Zacharias wanted an inquiry-based approach" (Haber-Schaim, 2006). Instead of using a textbook as the primary learning aid, Zacharias envisioned the course using any set of materials that were useful for learning by the students. These materials included "films, slides, textbooks, laboratory apparatus for students and teachers, homework, and ancillary reading" (Haber-Schaim, 2006). While revolutionary at the time, the ideas of Zacharias have been broadly accepted and implemented at all levels by the science education community. The NGSS and many state science standards—including South Carolina—contain statements related to students acting as scientists and using laboratory materials, from Kindergarten to the upper-level secondary courses. One of the lasting effects of the PSSC is the mainstream implementation of the scientific process into science courses, and this legacy has been carried by other instructional approaches.

Another important aspect of the PSSC were the foundational principles on which the curriculum rested. One crucial point was that "science was to be presented as a human endeavor" (Haber-Schaim, 2006), which allowed students to understand that anyone can do science. Another major facet was the selection of topics, and the PSSC chose a set of five essential ideas about science:

- The unity of physical science.
- The observation of regularities leading to the formulation of laws.
- The prediction of phenomena from laws.
- The limitations of laws.
- The importance of models in the development of physics. (Haber-Schaim, 2006)

These foundational ideas are still used today, most recently in the *Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (National Academy of Sciences, 2012). This framework establishes three dimensions—scientific and engineering practices, crosscutting concepts, and disciplinary core ideas—for science education, and these dimensions echo the ideas of Zacharias and work by the PSSC.

In the 1960s and 1970s, science education continued to evolve. One of the leaders during this era was Robert Karplus, a theoretical physicist and head of the Science

Curriculum Improvement Study (SCIS) at the University of California, Berkeley. Karplus developed a theoretical background for science education, and this "included the nature and development of children's intelligence, the nature and structure of science, and the implications of these two domains for designing science curricula" (Bybee, 2010). Karplus believed "the science curriculum had to provide students with experiences that differed from those they usually had, [and] the unique, unusual, and engaging experience afforded the opportunity for discovery" (Bybee, 2010). Utilizing psychological research from the work of Jean Piaget, Jerome Bruner, and others, Karplus and colleague Herb Thier created a practical program for students in grades K-6 through the SCIS. After performing work with the SCIS for a decade, Karplus solidified his ideas about science curriculum in a short talk titled *Three Guidelines for Elementary School Science* (1969). The first guideline was that

> two aspects of the teaching program should be distinguished from one another: the experiential—student experience with a wide variety of phenomena, including their acting on the materials involved; and the conceptual—introduction of the student to the approach which modern scientists find useful in thinking about the phenomena they study. (Karplus, 1969)

The second guideline stated that "major theories of intellectual development and learning should be drawn upon in curriculum construction" (Karplus, 1969), and the third guideline created a link between the first two.

> [SCIS has created] a learning cycle with three phases: *exploration*, which refers to self-directed, unstructured investigation; *invention*, which refers to the

introduction of a new integrating concept by teacher or by learner; and *discovery*, which refers to applications of the same new concept in a variety of situations, partly self-directed, partly guided. (Karplus, 1969)

During the exploration phase, "the learner [is allowed] to impose his ideas and preconceptions on the subject matter to be investigated" (Karplus, 1969). This will often lead to conflict between the results of the experiment and preconceptions, and the teacher learns information about the students' understanding. In the invention phase, conceptual information is provided to the students to reconcile the differences between experimental results and preconceptions. Finally, the discovery phase allows students to resolve any lingering differences by "establishing a new feedback pattern for his actions and observations" (Karplus, 1969). Repetition and practice occur at the conceptual level, leading to a deeper and more complete understanding of the phenomena. The idea of a "learning cycle continues to influence curriculum and instruction in science," and "it has substantial research support (Lawson, Abraham, and Renner 1989) and widespread application through textbooks on science teaching and learning (Lawson 1995; Marek and Cavallo 1997)" (Bybee, 2010).

Modeling Instruction began in the early 1980s from a partnership between Malcolm Wells, a high school physics and chemistry teacher, and David Hestenes, a theoretical physicist and physics education researcher at Arizona State University. Wells began his teaching career "with a powerful boost from PSSC and Harvard Project Physics teacher workshops in the heyday of Sputnik space-race fever," (Wells, Hestenes, & Swackhamer, 1995) and these workshops positively influenced his view towards teaching. Wells became a "hands-on" teacher, "always eager to build his own apparatus, and always looking for simple demonstrations of deep physics" (Wells, Hestenes, & Swackhamer, 1995). The high school in which Wells taught was near Arizona State University, and Wells participated in many university science and education courses throughout his high school teaching career. Eventually, Wells decided to complete his doctoral degree in physics education, and his advisor was Hestenes. Wells wanted to perform research that would greatly contribute to the field of physics education, and Wells and Hestenes discussed possibilities for several years. During the time of these discussions, Hestenes was also advising Ibrahim Halloun, a graduate student performing work on a *Mechanics Diagnostic* test. "This test measures the difference between [scientifically accepted] Newtonian concepts and the students' personal beliefs about the physical world" (Wells, Hestenes, & Swackhamer, 1995). Studies throughout many years have shown "that this difference is large, and conventional introductory physics courses are not effective at reducing the gap. Further, the results are independent of the instructor's qualifications and teaching style" (Wells, Hestenes, & Swackhamer, 1995). After using the *Mechanics Diagnostic* test with his students, Wells was shocked by how poorly students had performed. "Confronted by the dismal scores of his students on the *Diagnostic*, [Wells] soon concluded that the fault was in his teaching and set about doing better" (Wells, Hestenes, & Swackhamer, 1995). The decision by Wells to improve his teaching practice launched his doctoral research, and ultimately led to the creation of Modeling Instruction.

Wells "had already abandoned the traditional lecture-demonstration method in favor a student-centered inquiry approach based on the *learning cycle* popularized by Robert Karplus" (Wells, Hestenes, & Swackhamer, 1995) when he administered the *Mechanics Diagnostic* test. Wells deeply understood all aspects of the learning cycle from a university course in methods of science teaching; however, faced with the poor scores, Wells determined something essential was missing from the learning cycle. After reviewing work by Hestenes "proposing a theory of physics instruction with modeling as the central theme, ... Wells mastered the details ... [and] implemented the theory" (Wells, Hestenes, & Swackhamer, 1995). Wells created a version of Modeling Instruction that

> is laboratory-based and adapted to scientific inquiry. It emphasizes the use of models to describe and explain physical phenomena rather than solve problems. It aims to teach modeling skills as the essential foundation for scientific inquiry. To accomplish this in a systematic fashion, [Wells] developed the *modeling cycle*. (Wells, Hestenes, & Swackhamer, 1995).

By the end of Wells' doctoral work, the modeling method could "be described as *cooperative inquiry with modeling* structure and emphasis" (Wells, Hestenes, & Swackhamer, 1995). After further refinement over several years, "the modeling cycle has two stages, involving the two general classes of modeling activities: Model development and model deployment" (Wells, Hestenes, & Swackhamer, 1995). As a rough comparison with Karplus' work, "model development encompasses the exploration and invention stages of the learning cycle, while model deployment corresponds to the discovery stage" (Wells, Hestenes, & Swackhamer, 1995).

After the completion of the doctoral work and further refinement of Modeling Instruction, Wells, Hestenes, and others created summer workshops for teachers interested in this methodology. From 1989 to 2005, these workshops were funded by grants from the NSF; after 2005, a non-profit known as the American Modeling Teachers Association (AMTA) was formed to continue offering summer workshops and further develop curriculum. Resources for Modeling Instruction have been created for physics, chemistry, biology, and physical science, and the newest offering is for students in grades 6 through 8 (AMTA, 2015). Hestenes has continued to develop the theoretical foundations of Modeling Instruction, utilizing information and methods from philosophy and cognitive psychology (Hestenes, 2006; Hestenes, 2010).

Theory of Learning: Constructivism

During the 20th century and into the 21st century, the field of psychology has grown from a small number of experimental and theoretical researchers into a massive set of researchers. As advances in technology have enabled more detailed experiments within the field, additional theoretical work has been produced to generalize the results of the experiments and conceptualize the manner in which humans learn information. During the middle of the 20th century, behaviorism—using external stimuli to produce desired behaviors—was the dominant learning theory. Many in the field of education quickly implemented curriculum, instruction, and assessment practices that were based on behaviorism, and "schooling became structured around the premise that if teachers provided the correct stimuli, then students would not only learn, but their learning could be measured through observations of student behaviors" (Jones & Brader-Araje, 2002).

Introduction of these practices created a “behaviorist movement, [which] lead to a long series of strategies for schools such as management by objective, outcome-based education, and teacher performance evaluation systems” (Jones & Brader-Araje, 2002). However, “after years of implementation, behaviorism fell short on producing positive effects within the complex context of the classroom” (Jones & Brader-Araje, 2002), and educators began searching for alternative explanations of how humans learn.

Constructivism is an alternative theory of learning that “has emerged as one of the greatest influences on the practice of education in the last twenty-five years” (Jones & Brader-Araje, 2002). This is a theory of learning where

> learners are encouraged to *construct their own knowledge* instead of copying it from an authority, be it a book or teacher, *in realistic situations* instead of decontextualized, formal situations such as propagated in traditional textbooks, and *together with others* instead of on their own (Kanselaar, De Jon, Andriessen & Goodyear, 2001). (Kanselaar, 2002)

Although there are many closely-related definitions, “one of the common threads of constructivism that runs across all these definitions is the idea that development of understanding requires the learner to actively engage in meaning-making” (Jones & Brader-Araje, 2002). This is “in contrast to behaviorism” because “constructivists argue that ‘knowledge is not passively received but build up by the cognizing subject’ (von Glasersfeld, 1995). Thus, constructivists shift the focus from <u>knowledge as a product</u> to <u>knowing as a process</u>” (Jones & Brader-Araje, 2002).

Constructivism has two major historical strands, the first of which is attributed to Jean Piaget through his work in the mid-20th century. However, the underlying ideas have existed in earlier times, and one writer, Giambattista Vico, "declared in 1710 [that] 'the human mind can know only what the human mind has made' (von Glasersfeld, 1995, p. 21)" (Jones & Brader-Araje, 2002). Piaget's work—known as cognitive constructivism—emphasized that "the development of human intellect proceeds through adaptation and organization," where "adaptation is a process of assimilation and accommodation" into mental structures and organization is the process of linking mental structures (Kanselaar, 2002). "Furthermore, Piaget's constructivist stances are seen in his belief that our understandings of reality are constantly being revised and re-constructed through time and with respect to exposure to new experiences" (Jones & Brader-Araje, 2002). The second strand—social-cultural constructivism—was established by Lev Vygotsky and challenges the notion of individuality embedded in the Piagetian strand of constructivism. Vygotsky argued that "the path between objects and thought is mediated by other people through the use of signs or the symbols of language (Veer & Valsiner, 1993, p. 220)" and "that all higher mental functions are social in origin and embedded in the context of the sociocultural setting" (Jones & Brader-Araje, 2002).

The underlying idea of constructivism—that learning is negotiated meaning-making—has become embedded in school pedagogy, particularly in science. In the National Science Education Standards, a set of science standards that preceded the NGSS, the National Research Council states that

> An important stage of inquiry and of student science learning is the oral and written discourse that focuses the attention of students on how they know what they know and how their knowledge connects to larger ideas, other domains, and the word [sic] beyond the classroom. … Using a collaborative group structure, teachers encourage interdependency among group members, assisting students to work together in small groups so that all participate in sharing data and in developing group reports. (National Research Council, 1996, p.36) (Jones & Brader-Araje, 2002)

The NGSS has similar statements that related to constructivist ideas, especially in the area of science and engineering practices.

Another manner in which constructivist pedagogy may be determined in the classroom is by examining the learning environment.

> Jonassen (1994) proposed that there are eight characteristics that differentiate constructivist learning environments:
>
> 1. They provide multiple representations of reality.
> 2. Multiple representations avoid oversimplification and represent the complexity of the real world.
> 3. They emphasize knowledge construction instead of knowledge reproduction.
> 4. They emphasize authentic tasks in a meaningful context rather than abstract instruction out of context.

5. They provide learning environments such as real-world settings or case-based learning instead of predetermined sequences of instruction.
6. They encourage thoughtful reflection on experience.
7. They enable context- and content-dependent knowledge construction.
8. They support collaborative construction of knowledge through social negotiation, not competition among learners for recognition. (Kanselaar, 2002)

The theoretical base of Modeling Instruction is consistent with seven of the eight—missing number five—characteristics proposed by Jonassen; Modeling Instruction has a predetermined sequence of instruction that builds upon itself so that students may connect previous learning to new learning.

Theoretical Base of Modeling Instruction

As scientists perform research on cognitive processes with increasingly sophisticated tools, the understanding of how humans learn continues to improve. Advances in the fields of neuroscience and cognitive psychology have provided relevant information for teachers and implications for curriculum design, and it seems that the best curricula will match the manner in which students learn. David Hestenes has created a theoretical foundation for Modeling Instruction that matches modern cognitive theory, though the foundation of the theory began with a question: "Why don't [university scientists] evaluate their teaching practices with the same critical standards they apply to scientific research?" (Hestenes, 1987). For Hestenes,

> the ultimate goal of pedagogical research should be to establish a mature instructional theory which consolidates and organizes a nontrivial body of knowledge about teaching. Without such a theory, little pedagogical knowledge can be transmitted between generations of teachers, teachers cannot improve without repeating mistakes of their predecessors, and only the most capable and dedicated can progress to teaching with a moderate degree of insight and subtlety. (1987)

As pedagogical research has occurred in the field of Physics Education Research (PER), many groups have created instructional strategies to improve the understanding of students (Beichner, 2009). A principle concern of those in the PER community "has been to establish a scientific theory of instruction to guide research and practice" (Hestenes, 2006), and Hestenes has integrated philosophical, scientific, and cognitive theories to serve as a foundation for Modeling Instruction. The work of Hestenes has

> identified construction and use of conceptual models as central to scientific research and practice, so [Hestenes] adopted it as the thematic core for a MODELING THEORY of science instruction. From the beginning, it was clear that Modeling Theory had to address cognition and learning in everyday life as well as in science, so it required development of a model-based epistemology and philosophy of science. (Hestenes, 2006)

To provide connections with modeling theory of cognition, modeling theory of scientific knowledge must have several key terms defined:

- System: A set of related objects. "Systems can be of any kind depending on the kind of object. … In a *conceptual system* the objects are *concepts*. In a *material system* the objects are material *things*" (Hestenes, 2006).
- Structure: "The set of relations among objects in the system" (Hestenes, 2006). In science, "all material systems have geometric, causal and temporal structure, and no other (metaphysical) properties are needed to account for their behavior" (Hestenes, 2006). As stated by modeling theory, "science comes to know objects in the real world not by direct observation, but by constructing conceptual models to interpret observations and represent the objects in the mind. This epistemological precept is called *Constructive Realism* by philosopher Ronald Giere" (Hestenes, 2006).
- Model: "A *representation of* ***structure*** in a material system, which may be real or imaginary" (Hestenes, 2006). Models exist in many different ways, depending on their function. "All models are idealizations, representing only structure that is *relevant* to the purpose, not necessarily including all five types of structure" (Hestenes, 2006). Figure 2.1 provides a summary of the possible types of structure.

(a) **systemic structure**:
- ***composition*** (internal parts (objects) in the system)
- ***environment*** (external agents linked to the system)
- ***connections*** (external and internal links)

(b) **geometric structure:**
- ***position*** with respect to a reference frame (external)
- ***configuration*** (geometric relations among the parts)

(c) **object structure**:
- intrinsic properties of the parts

(d) **interaction structure:**
- properties of (causal) links

(e) **temporal (event) structure**:
- temporal change in structure of the system

Figure 2.1. Structures of a conceptual model in modeling theory of scientific knowledge. From "Notes for a Modeling Theory of Science, Cognition and Instruction" by D. Hestenes, 2006, *Proceedings of the 2006 GIREP Conference*. Copyright 2006 by David Hestenes. Reprinted with permission.

From these definitions many models may be created, and including two useful models for scientific knowledge: A mathematical model, representing the structure of a system by state and interaction variables; and, a process model, designating temporal structure as a change of state variables. These two models form the foundation of scientific theory, which is defined as "a system of general principles (or **Laws**) specifying a class of state variables, interactions and dynamics" (Hestenes, 2006). Scientific process is governed by general laws that define the domain and structure of a theory and specific laws defining models. "The *content* of a scientific theory is a population of validated models," and a "model is *validated to the degree* that the measured values (data) match predicted values determined by the model" (Hestenes, 2006).

With the definitions of a conceptual model, a modeling theory of cognition may be created. Figure 2.2 provides information about the connection between the physical, mental, and conceptual worlds, and the theory rests on a "crucial distinction between

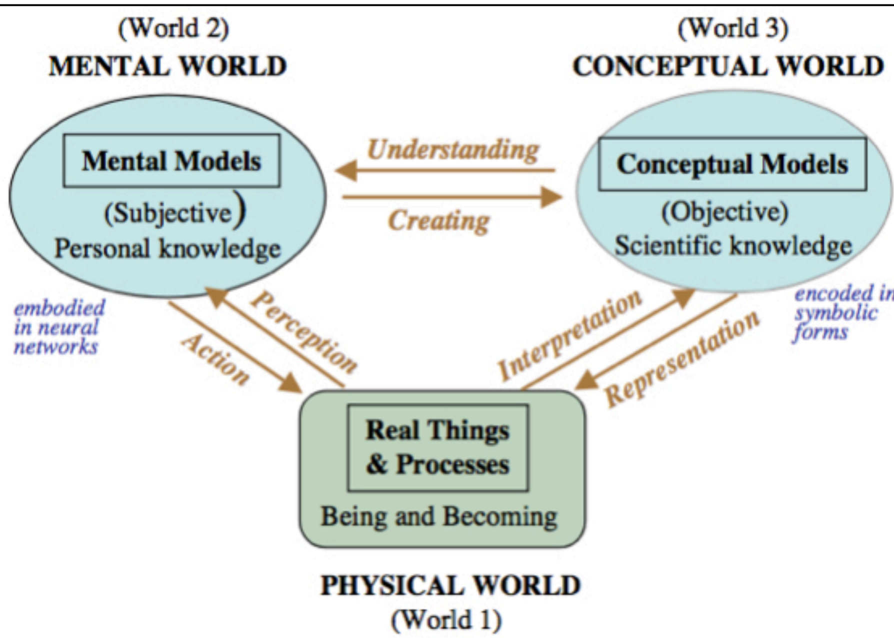

Figure 2.2. Relationships between the physical, mental, and conceptual worlds (Hestenes, 2006, p. 10). From "Notes for a Modeling Theory of Science, Cognition and Instruction" by D. Hestenes, 2006, *Proceedings of the 2006 GIREP Conference*. Copyright 2006 by David Hestenes. Reprinted with permission.

mental models and conceptual models … Mental models are private constructions in the mind of an individual" (Hestenes, 2006). Conceptual models are an encoded "model structure in symbols that activate the individual's mental model and corresponding mental models in other minds" (Hestenes, 2006). Connections between the three worlds highlight the manner in which they interact, and an understanding of these relationships provide an opportunity to connect the modeling theory of cognition with the modeling theory of scientific knowledge. The combination of modeling theories of scientific knowledge and cognition is simply known as modeling theory. Figure 2.3 describes how modeling theory drives instructional design, which informs teaching practice.

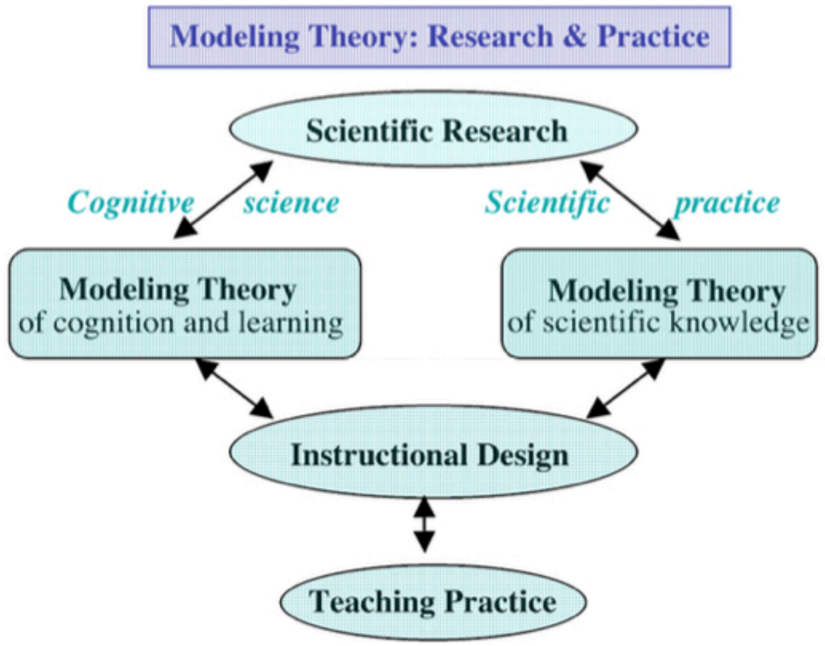

Figure 2.3. Relationships between modeling theory, cognition and learning, scientific knowledge, instructional design, and teaching practice. From "Notes for a Modeling Theory of Science, Cognition and Instruction" by D. Hestenes, 2006, *Proceedings of the 2006 GIREP Conference*. Copyright 2006 by David Hestenes. Reprinted with permission.

As indicated by the arrows in Figure 2.3, Modeling Instruction—the combination of instructional design and teaching practice—arises from modeling theory. "Modeling Instruction produces students who engage intelligently in public discourse and debate about matters of scientific and technical concern … and students in modeling classrooms experience first-hand the richness and excitement of learning about the natural world" (Jackson, Dukerich, & Hestenes, 2008). Modeling Instruction is based on the coherent instructional objectives, which are:

- To engage students in understanding the physical world by ***constructing and using scientific models*** to describe, to explain, to predict, to design and control physical phenomena.

- To provide students with ***basic conceptual tools*** for modeling physical objects and processes, especially mathematical, graphical and diagrammatic representations.
- To familiarize students with a small set of basic models as the ***content core*** of physics [and chemistry, biology, and physical science].
- To develop insight into the ***structure*** of scientific knowledge by examining how *models* fit into *theories*.
- To show how scientific knowledge is ***validated*** by engaging students in *evaluating* scientific models through comparisons with empirical data.
- To develop skill in all aspects of modeling as the ***procedural core*** of scientific knowledge. (Wells, Hestenes, and Swackhamer, 1995)

Modeling Instruction also has a student-centered instructional design, whereby

- Instruction is organized into ***modeling cycles*** which engage students in all phases of model development, evaluation and application in concrete situations—thus promoting an integrated understanding of modeling processes and acquisition of coordinated modeling skills.
- The teacher sets the stage for student activities, typically with a demonstration and class discussion to establish common understanding of a question to be asked of nature. Then, in small groups, students ***collaborate*** in planning and conducting experiments to answer or clarify the question.

- Students are required to present and justify their conclusions in oral and/or written form, including a ***formulation*** of models for the phenomena in question and ***evaluation*** of the models by comparison with data.
- Technical terms and representational tools are introduced by the teacher as they are needed to sharpen models, facilitate modeling activities and improve the quality of discourse.
- The teacher is prepared with a definite ***agenda*** for student progress and ***guides*** student inquiry and discussion in that direction with "Socratic" questioning and remarks.
- The teacher is equipped with a ***taxonomy*** of typical student misconceptions to be addressed as students are induced to articulate, analyze and justify their personal beliefs. (Wells, Hestenes, & Swackhamer, 1995)

As a framework for organizing instruction, the modeling cycle is instrumental for students to develop appropriate models that accurately describe the phenomena they study. The modeling cycle has two distinct parts: Model development, in which students perform a paradigm laboratory and engage in discussions to create a mental and conceptual model related to the physical world; and model deployment, during which students manipulate and test the model to determine the limits and applicability of the model. Throughout model deployment, students utilize written and verbal, graphical, diagrammatic, and mathematical representations to test the model. Assessments in the form of whiteboarding, quizzes, and additional laboratories are used formatively, and the modeling cycle is completed with a laboratory practicum and summative unit assessment.

One major aspect that separates Modeling Instruction from other instructional varieties is whiteboarding. The whiteboards are 24” x 36” erasable pieces that students use during all parts of the modeling cycle, giving students the opportunity to make their thinking visible around scientific content and processes. When performing laboratories, students record, graph, and analyze data on their whiteboard for presentation during the post-lab discussion. Having visible information from all groups allows students to compare, contrast, and question data and analysis easily, creating a robust discussion about the results. As students solve problems, “small groups of students write up their results … [and] have to account for everything they do in solving a problem” (Jackson, Dukerich, & Hestenes, 2008). The students who are presenting are questioned by other students and the instructor to explicitly articulate their understanding, and any misconceptions are corrected through Socratic questioning.

Methodology

The research question for this study will be: What is the effect of Modeling Instruction on the achievement of students in AP Physics C: Mechanics and Electricity and Magnetism? To collect data related to this question, the study will utilize both a one-group pretest-posttest design and one-shot case study. Baseline information collected from students is:

- the final numerical grade from the highest mathematics and science courses taken by the student.
- DEOC or AP scores from the highest mathematics and science courses taken by the student.

For the one-group pretest-posttest method, student information is collected on the:

- 2015 AP Physics C: Mechanics practice exam.
- Force Concept Inventory (FCI).
- Mechanics Baseline Test (MBT).
- 2015 AP Physics C: Electricity and Magnetism practice exam.
- Brief Electricity and Magnetism Assessment (BEMA).

In the one-shot case study, student final numerical grades in AP Physics C: Mechanics and Electricity and Magnetism and scores from the 2017 AP Physics C: Mechanics and Electricity and Magnetism exams are collected. Simple statistical analysis—mean, median, standard deviation, range—is performed on the AP exams, FCI, MBT, and BEMA, and correlations are made between scores on these assessment and baseline information. There are no known studies that provide student scores in the 2015 AP Physics C: Mechanics or Electricity and Magnetism exams; however, there is literature related to the FCI, MBT, and BEMA.

The FCI was created by David Hestenes, Malcolm Well, and Gregg Swackhamer, and this inventory was designed “to probe student belief on [force] and how these beliefs compare with the many dimensions of the Newtonian concept” (Hestenes, Wells, & Swackhamer, 1992). The FCI “requires a forced choice between Newtonian concepts and commonsense alternatives,” and results from the inventory are “a very good detector of Newtonian thinking” (Hestenes, Wells, & Swackhamer, 1992). The FCI contains 30 questions, and these are arranged into 6 categories of Newtonian Concepts: Kinematics, first law, second law, third law, superposition principle, and kinds or force. “All six [conceptual dimensions] are required for the complete concept," and "each dimension is probed by questions of more than one type" (Hestenes, Wells, & Swackhamer, 1992).

To accompany the FCI, David Hestenes and Malcolm Wells created the MBT, also known as the Baseline. "Questions on the [FCI] were designed to be meaningful to students without formal training in mechanics and to elicit their preconceptions about the subject. In contrast, the Baseline emphasizes concepts that cannot be grasped without formal knowledge of mechanics" (Hestenes & Wells, 1992). The MBT asks questions on the following parts of mechanics: Linear motion and curvilinear motion in kinematics; first law, second law with and without dependence on mass, third law, superposition principle, work-energy, energy conservation, impulse-momentum, and momentum conservation in general principles; and gravitational free-fall and friction in specific forces. On the surface level,

> the Baseline looks like a conventional quantitative, problem-solving test, though its main intent is to assess qualitative understanding. The multiple-choice distractors in the Baseline are not commonsense alternatives as they are in the Inventory, though they include typical student mistakes, which are more often due to deficient understanding than to carelessness. We excluded problems that can be solved by a simple "plug-in" of numbers into a formula. (Hestenes & Wells, 1992)

Because "the two tests are complementary probes for understanding of the most basic Newtonian concepts," taking the information from the FCI and MBT gives "a fairly complete profile of [student] understanding" (Hestenes & Wells, 1992).

The BEMA “was developed in 1997 by [Ruth] Chabay and [Bruce] Sherwood, aided by Fred Reif, to measure students’ qualitative understanding and retention of basic concepts in electricity and magnetism” (Ding, Chabay, Sherwood, & Beichner, 2006). The assessment “is a 30-item multiple choice test which covers the main topics discussed in both the traditional calculus-based [electricity and magnetism] (E&M) physics curriculum and the matter and interactions curriculum” (Ding et al., 2006). Instead of probing particular E&M concepts in detail, “the test was designed to incorporate broad coverage of elementary E&M” (Ding et al., 2006). Using data from a sample of undergraduate students at Carnegie Mellon University and North Carolina State University, five statistical tests were performed: “Three measures focusing on individual test items (item difficulty index, item discrimination index, item point biserial coefficient) and two measures focusing on the test as a whole (test reliability and test Ferguson’s)” (Ding et al., 2006). Results from these measures “indicate that BEMA is a reliable test with adequate discriminatory power” (Ding et al., 2006), allowing use in other traditional and action research studies.

Previous Research Results

Modeling Instruction has been implemented most frequently in high school physics courses, with over 3,000 teachers participating in summer workshops from 1995 to the present. The FCI "has become the most widely used and influential instrument for assessing the effectiveness of introductory physics instruction" (Jackson, Dukerich, & Hestenes, 2008), and the aggregate of these scores shows a large effect of Modeling Instruction on the achievement of students in physics courses versus a much smaller effect of traditional instruction. Figure 2.4 "summarizes data from a nationwide sample of 7500 high school physics students involved in the *Modeling Instruction Project* during 1995-98" (Hestenes, 2006).

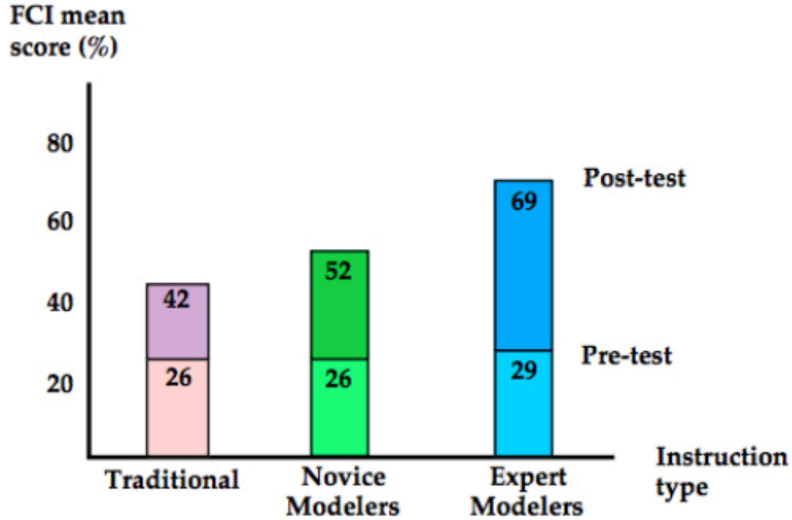

Figure 2.4. FCI mean pretest and posttest scores under different instruction types. From "Notes for a Modeling Theory of Science, Cognition and Instruction" by D. Hestenes, 2006, *Proceedings of the 2006 GIREP Conference*. Copyright 2006 by David Hestenes. Reprinted with permission.

The average pretest mean is slightly above a random guessing mean of 20%, and the data show that "traditional high school instruction (lecture, demonstration, and standard laboratory activities) has little impact on student beliefs" (Jackson, Dukerich, & Hestenes, 2008). Novice Modelers, defined as those in their first year teaching with Modeling Instruction, achieved a mean posttest FCI score of 51%. Those using Modeling Instruction for two or more years were defined as Expert Modelers, and their mean posttest FCI score was 69%. Teachers from other workshops have also given the FCI to their students, and there exists "many examples of [modeling teachers] who consistently achieve posttest means from 80-90%" (Hestenes, 2006).

The seminal study for Modeling Instruction is summarized by Wells, Hestenes, and Swackhamer (1995), and the research was performed by Malcolm Wells for his dissertation. Wells had established an inquiry course, whereby "70% of class time was devoted to lab activities, which were either developed by Malcolm or modified from the Harvard Project Physics handbook" (Wells, Hestenes, & Swackhamer, 1995). The other "30% of class time was devoted to in-class study groups utilizing the PSSC fourth-edition textbook," and "problems for class and homework were selected from the textbook or designed by Malcolm to reinforce and expand on concepts developed in the lab activities" (Wells, Hestenes, & Swackhamer, 1995). As Wells designed the modeling course, his class could "be described as cooperative inquiry with modeling structure and emphasis. ... The instructional difference [with the inquiry course] resided in the systematic emphasis on models and modeling," and "the net result was an increase in coherence of the whole course and its subject" (Wells, Hestenes, & Swackhamer, 1995). The inquiry course and modeling course became two of the groups in Wells' dissertation research, and the third course was led by a teacher who "was well matched to Malcolm in regard to age, experience, training and dedication" (Wells, Hestenes, & Swackhamer, 1995). This teacher used a typical textbook, and "his course consisted of lectures and demonstrations (80% of class time), with homework questions and problems selected to reinforce important concepts from lecture and to provide practice in problem solving" (Wells, Hestenes, & Swackhamer, 1995). In contrast to Wells, the traditional teacher devoted 20% of class time to laboratory activities; rather than allowing students to explore, these laboratory activities "were designed and/or selected to emphasize important concepts from lectures and/or to develop laboratory skills" (Wells, Hestenes, & Swackhamer, 1995).

For the study, "all three high school courses (inquiry, modeling, and traditional) were honors courses with about 24 students in each. By prior agreement between the teachers, all three covered the same topics in mechanics on nearly the same time line" (Wells, Hestenes, & Swackhamer, 1995). Using a pretest-posttest experimental design with the *Mechanics Diagnostic* as the test, Wells and the traditional teacher assessed their classes at the beginning and end of mechanics. The data in Table 1 "strongly supports the conclusions that Malcolm's modeling method is a considerable improvement over his cooperative inquiry method and clearly superior to the traditional method" (Wells, Hestenes, & Swackhamer, 1995). The modeling course has a 34% increase between the pretest and posttest, which is almost three times the 13% increase of the traditional course This "is a large effect, because the standard deviation of student scores does not exceed 16% for any of the classes" (Wells, Hestenes, & Swackhamer, 1995).

Table 2.1

Comparison of Student Pretest and Posttest Mean Scores on the Mechanics Diagnostic

Course	Pretest Mean	Posttest Mean	Percent Increase
Traditional	44	57	13
Inquiry	31	53	22
Modeling	38	72	34

Note. Adapted from "A Modeling Method for High School Physics Instruction," by M. Wells, D. Hestenes, and G. Swackhamer, 1995, *American Journal of Physics*, *63*(7), p. 610. Copyright 1995 by David Hestenes. Reproduced with permission.

A recent study on the effect of Modeling Instruction in a Louisiana high school classroom was conducted by Mark Arseneault (2014). Arseneault taught two classes with traditional instruction and two classes with Modeling Instruction, and each instructional group contained one regular physics class and one honors class. The four classes received equal amounts of time on topics, and Arseneault utilized a pretest-posttest design with the FCI as the test. The traditional classes had a pretest mean of 24% and the Modeling Instruction classes had a pretest mean of 28%, both of which are slightly higher than the random mean of 20%. However, the traditional classes had a posttest mean of 34%, yielding an increase of 10% from the pretest to posttest. The Modeling Instruction classes had a posttest mean of 45%, giving an increase of 17% between the pretest and posttest. Whereas these results are not as impressive as those obtained by Wells, they are consistent with the results in Figure 2.4 from Novice Modelers. Overall, data from studies on Modeling Instruction have consistently shown a higher increase in student performance on the FCI and other assessments than other instructional methods. As a result, "a U.S. Department of Education Expert Panel in Science recognized the Modeling Instruction Program as one of only two exemplary K-12 science programs out of 27 programs evaluated (U.S. Department of Education, 2001)" (Jackson, Dukerich, & Hestenes, 2008).

For dissertation research, Eric Brewe incorporated Modeling Instruction into "the Calculus-based Physics class in the Freshmen Integrated Program in Engineering (FIPE) at Arizona State University" (Brewe, 2002) and analyzed scores on common exam problems and the FCI for this group and a comparison group. "The comparison group is a

Calculus-based Physics course for engineers at North Carolina State University," and "the students in this class are primarily first-year engineers" (Brewe, 2002). Unfortunately, the FCI pretest scores were significantly different between the groups, so "the initial assumption that the groups were roughly equivalent is invalid" (Brewe, 2002). However, "the FIPE group had a higher posttest score, and showed higher gains, therefore taking a minimal view, at least the FIPE students received a reasonable treatment of force concepts" (Brewe, 2002). For the common exam problem analysis, the FIPE students outperformed the comparison group. "The class means for both Problem #1 and Problem #2 were significantly different at the .01 level" (Brewe, 2002), which indicates Modeling Instruction had an impact on the problem-solving ability of students.

There are few studies that discuss AP Physics C: Mechanics and Electricity and Magnetism, and no studies that include Modeling Instruction pedagogy. This study will contribute to the research base by clarifying the underlying theory of Modeling Instruction and showing results from the implementation of Modeling Instruction in AP Physics C.

Modeling Instruction and Equity

Whereas there are few formally published studies that focus exclusively on Modeling Instruction and equity at the high school level, many of the studies in this literature review provide information related to students in non-honors or lower-level courses. If the assumption is made that students in the non-honors courses had little success in science and mathematics throughout their academic career, then a goal of subsequent science and mathematics courses should be to provide opportunities for success. Through the student-centered and inquiry-based design, Modeling Instruction offers a different way to learn in a science course; many of the students in non-honors courses are more successful in courses that utilize non-traditional methods of instruction. In the study by Wells, Hestenes, & Swackhamer (1995), Wells and the traditional teacher had students in both non-honors and honors courses. On the FCI, the non-honors course for the traditional teacher had a pretest mean of 27% and a posttest mean of 48% for a 21% increase. However, non-honors course for Wells had a pretest mean of 28% and a posttest mean of 64% for a 36% increase. This posttest mean of 64% also outperformed the traditional teacher's posttest mean of 56%, showing that Modeling Instruction greatly impacts student performance regardless of previous performance by students.

In an unpublished study, Javier Melendez and David Wirth implemented Modeling Instruction in an integrated algebra and physics course "to 9th grade Hispanic and black students at Tolleson High School, a largely minority public school in urban Phoenix [Arizona]" (Melendez & Wirth, 2001). The students in this course had two 90-minute blocks daily, and "the teachers identified the use of Modeling Instruction, the integrated approach, and the extended time (thus enabling the students to become a learning community) as the three most important factors in their success" (Melendez & Wirth, 2001). Two evaluations were used: A district end of year achievement test and the FCI. On the district end of year test, students in this class scored higher than students in a traditional honors ninth grade algebra class. On the FCI, the students' posttest mean was 61%; this value is slightly above the Newtonian threshold and comparable to Modeling Instruction honors physics courses for seniors. Results from these studies show promise for the use of Modeling Instruction with students having lower background science and mathematics knowledge.

At the university level, Brewe et al. implemented Modeling Instruction in introductory calculus-based physics at Florida International University as a part of “extensive efforts to increase the number of historically under-represented students in physics and science” (2010). Students in a lecture-based introductory calculus-based physics course and the Modeling Instruction-based course were assessed with the FCI in a pretest-posttest model, and the researchers calculated the raw gain—posttest score minus pretest score—for each student. The overall mean raw gain for students in the lecture-based course was 14.8, whereas the students in the Modeling Instruction-based course had an overall mean raw gain of 30.4. The researchers also found that students from under-represented groups—women, Black, Hispanic, and Native American—had similar results, with a mean raw gain for students in the lecture-based course of 15.0 and students in the Modeling Instruction-based course had mean raw gain of 30.0. “The significant differences across all these different groups in the post-test FCI and Raw Gain indicated that the [Modeling Instruction] approach benefits all students” (Brewe et al., 2010). Results from studies in high school and at the university level suggest that Modeling Instruction is beneficial for all students, especially for those from groups that have been under-represented in physics courses and as physics majors.

Conclusion

Constructivism is a theory of learning that describes the manner in which humans build understanding from previous knowledge and new information, and this theory provides ideas related to the structure of education. Modeling theory provides a foundation for how humans learn scientific concepts, leading to the manner in which science should be taught. Modeling Instruction has been created to align curriculum, instruction, and assessment with modeling theory, supplying a way to address student misconceptions and create accurate learning for each student. The documents selected for this literature review have been chosen to provide context for the problem of practice and research question. This study is part of the broader movement to improve science education, and extends the research base in Modeling Instruction, PER, and Action Research. There are no available studies that examine the impact of Modeling Instruction on students in AP Physics C: Mechanics and Electricity and Magnetism, so this study will make a unique contribution to the field.

Keywords

Brief Electricity and Magnetism Assessment (BEMA): 30-item assessment that determines "students' qualitative understanding and retention of basic concepts in electricity and magnetism" (Ding et al., 2006).

Conceptual model: An encoded "model structure in symbols that activate the individual's mental model and corresponding mental models in other minds" (Hestenes, 2006).

Constructivism: A theory of learning with "a central idea is that human knowledge is *constructed*, that learners build new knowledge upon the foundation of previous learning" (Kanselaar, 2002).

Force Concept Inventory (FCI): 30-item assessment that determines conceptual understanding on the topic of force (Hestenes, Wells, & Swackhamer, 1992).

Learning cycle: A method of curriculum design that was aligned with cognitive research and popularized by Robert Karplus and the SCIS (Karplus, 1969); the three parts of the learning cycle are exploration, invention, and discovery.

Mechanics Baseline Test (MBT): 30-item assessment that determines conceptual understanding of mechanics (Hestenes & Wells, 1992).

Mathematical model: A way of representing the structure of a system by state and interaction variables (Hestenes, 2006).

Mental models: Private constructions in the mind of an individual (Hestenes, 2006).

Model: "A representation of structure in a material system, which may be real or imaginary" (Hestenes, 2006).

Modeler: Informal term for person who uses Modeling Instruction.

Modeling cycle: A method of curriculum design that is aligned with cognitive research and used in Modeling Instruction (Jackson, Dukerich, & Hestenes, 2008); the two parts of the modeling cycle are model development and model deployment.

Modeling Instruction: Combination of modeling theory and instructional practices that create a coherent conceptual understanding for students; process by which science is performed and understood.

Normalized gain: Mathematical equation that describes the growth of an individual student on an assessment (Hake, 1998).

Pedagogy: Method and practice of teaching.

Physics Education Research: Set of researchers working towards a coherent pedagogy of physics instruction (Beichner, 2009).

Process model: A way of designating temporal structure as a change of state variables (Hestenes, 2006).

Scientific process: Method by which science is constructed; this process is governed by general laws that define the domain and structure of a theory and specific laws defining models (Hestenes, 2006).

Structure: “The set of relations among objects in the system” (Hestenes, 2006).

System: A set of related objects; “systems can be of any kind depending on the kind of object. … In a conceptual system the objects are concepts. In a material system the objects are material things” (Hestenes, 2006).

CHAPTER 3 – METHODOLOGY

Modeling Instruction in a curricular organization and instructional strategy that places models at the center of science learning. Constructivist principles and modeling theory form the philosophical foundation of Modeling Instruction, and the modeling cycle provides a way for students to create and modify models. Many studies with high school students have indicated that Modeling Instruction allows students to understand science more thoroughly than other curricular or instructional strategies, but there are few studies using Modeling Instruction with university physics and no studies discussing the incorporation of Modeling Instruction with AP Physics C: Mechanics and Electricity and Magnetism. The problem of practice for this study is to incorporate Modeling Instruction into AP Physics C: Mechanics and Electricity and Magnetism and determine the effect of Modeling Instruction on student achievement in AP Physics C: Mechanics and Electricity and Magnetism. To characterize the results of the problem of practice, quantitative methods are used in an action research paradigm.

The problem of practice for this is inadequate student achievement in AP Physics C: Mechanics and Electricity and Magnetism, and the proposed solution is to incorporate Modeling Instruction theory and practice in the researcher's courses during the 2016-2017 school year. To make the AP Physics C: Mechanics and Electricity and Magnetism courses better for 2016-2017 school year, the researcher is switching to a full Modeling Instruction organization so that students will have higher achievement on the 2017 AP

Physics C: Mechanics and Electricity and Magnetism exams, strong achievement on the evaluation instruments, and solid conceptual understanding for their future STEM courses.

Because the effect of Modeling Instruction methods and theory on the student achievement in AP Physics C: Mechanics and Electricity and Magnetism is unknown, the research question for this dissertation is the following: What is the effect of Modeling Instruction on the achievement of students in AP Physics C: Mechanics and Electricity and Magnetism?

The purpose of the present Action Research study is to determine the efficacy of Modeling Instruction in AP Physics C for twenty students in a suburban high school in South Carolina. The specific purpose of the study is to (a) clarify the cognitive theory underlying Modeling Instruction and connect this theory to general learning principles, (b) update current Modeling Instruction models to explicitly include properties, calculus-based mathematical representations, other representations, rules of behavior, and sequence of activities and information, and (c) create new models for topics outside the standard Modeling Instruction materials with properties, representations, rules of behavior, and sequence of activities. The general purpose is to contribute to the knowledge base within Physics Education Research (PER) for the topics of Modeling Instruction and AP Physics C.

Action Research Design

This study utilizes a quantitative action research design because the researcher is interested in understanding the magnitude of the impact Modeling Instruction has on student achievement in AP Physics C: Mechanics and Electricity and Magnetism.

The participants of this study are students in the researcher's AP Physics C: Mechanics and Electricity and Magnetism courses, and demographics and other pertinent information will be included when the courses are established.

The site for this study will be a large, suburban high school in the southeastern part of the United States. The high school has a student body of over 4,000 students, and the ethnic composition is 82% Caucasian, 12% African-American, 3% Hispanic, and 3% other. Approximately 37% are served by gifted and talented program, and 6% are classified as students with disabilities. The high school has received an absolute rating of "Excellent" from the state Department of Education from 2010 to 2014, and offers over 250 courses. These range from dance, choir, theatre, and band in the performing arts, engineering, mechatronics, horticulture, and others in the career and technical fields, and a comprehensive selection in mathematics, science, English, and social studies. The school has been very successful in many aspects: Academically, members of the class of 2015 were awarded over 24 million dollars in scholarships, 252 students received recognition from their performance on Advanced Placement (AP) tests, one senior was named National Merit Finalist, and eight seniors received appointments to a military academy; athletically, the school was named the 2014-2015 recipient of the state Athletic Administrators Association Director's Cup for Class AAAA, given to the school with the best combined performance of all sports; and in the performing arts and career and technical education clubs, school's Marching Band won its ninth State Championship and finished seventh in the Grand Nationals competition, and the Culinary Arts Management Team won both the state and national competition. Many other clubs and teams achieved a high level of success, driven by dedicated and talented students, teachers, and coaches.

The community is a coastal area with a historically conservative population, though the area has received an influx of new residents in the last 10 years. This rapid population expansion has caused an increase in traffic delays and general congestion, an increase in the number of new homes and commercial developments, and overcrowding at the research site. The community has an overwhelming ethnicity of Caucasians, but there are pockets of African-Americans and other ethnic groups. The research site has received many financial and time commitments from a diverse group of members of the community, and a positive interaction exists between the research site and community.

As the researcher and students progress through the course, the researcher will build trust by sharing information related to models and course sequence. The researcher will also explain constructivist and modeling theories so that students understand the manner in which the course is constructed and gain a deeper appreciation of the structure underlying physics. As data is collected at the end of each course, information will be shared with students so they may understand how well they did on the assessments. Students will also reflect on their effort and mental models to consolidate their learning so they can be successful in future science courses.

Positionality

In action research, the researcher is intimately involved in all aspects of the work. The inspiration for the research comes from a personal problem of practice and is a topic that is meaningful for the researcher. Due to the highly personal nature of action research, bias could be induced during the creation of the research plan, implementation, and analysis. The researcher must be diligent to notice and extinguish any bias towards the participants or results and maintain a high level of ethics.

When performing any research, ethical considerations must remain in focus during the stages of research. "Keeping caring, fairness, openness, and truth at the forefront of your work as a teacher-inquirer is critical to ethical work" (Dana & Yendol-Hoppey, 2014). A major consideration for this study is privacy, because data about the participants will be collected to use during analysis. Personal identification will never be associated with a particular student when collecting the data, and student data will be reported in the aggregate to further ensure students cannot be individually identified. The district in which the study is conducted explicitly provides an opportunity for students and employees to opt out of any research without penalty, and also protects students from possible physical, psychological, legal or other risks.

Another area of concern is the curricular organization and instruction students will receive. This dissertation proposes to use a teaching method that is different from other science pedagogy at the research site, so there could be an issue for students who do not want to participate in the study. However, in all documents found for the literature review, there is no case where students receiving Modeling Instruction have performed more poorly than the student receiving traditional or inquiry-based instruction. If this research shows positive effects on student achievement, the benefit to all future AP Physics C students outweighs any potential risks of this research.

Data Collection and Analysis

This study utilizes two different quantitative Action Research designs: A one-group pretest-posttest method and a one-shot case study. For the one-group pretest-posttest method, student information is collected on the:

- 2015 AP Physics C: Mechanics practice exam: 1.5-hour assessment, administered at the beginning and end of the fall 2016 semester
- Force Concept Inventory (FCI): 0.5-hour assessment, administered at the beginning and end of the fall 2016 semester
- Mechanics Baseline Test (MBT): 0.5-hour assessment, administered at the beginning and end of the fall 2016 semester
- 2015 AP Physics C: Electricity and Magnetism practice exam: 1.5-hour assessment, administered at the beginning and end of the spring 2017 semester
- Brief Electricity and Magnetism Assessment (BEMA): 0.5-hour assessment, administered at the beginning and end of the spring 2017 semester

In the one-shot case study, student final numerical grades for AP Physics C: Mechanics and Electricity and Magnetism and scores from the 2017 AP Physics C: Mechanics and Electricity and Magnetism exams are collected. Additionally, baseline information is collected from students:

- Final numerical grade from the highest mathematics and science courses taken by the student.
- DEOC or AP scores from the highest mathematics and science courses taken by the student.

Because this action research only has one group, data collected from the instruments will be analyzed with simple statistics: Mean, median, standard deviation, and range. This information is congruent with data from documents in the literature review, and data from previous studies is used as a comparison with the data from this research. Normalized gain, defined as a mathematical equation that describes the growth of an individual student on an assessment and given by the equation $G = \frac{posttest\,\% - pretest\%}{100 - pretest\,\%}$ (Hake, 1998), will be calculated and reported for the AP Physics C: Mechanics practice exam, FCI, MBT, AP Physics C: Electricity and Magnetism practice exam, and BEMA. Correlations between baseline data and each assessment are performed to provide more information during future studies.

Conclusion

The research paradigm for this study is quantitative action research, and the problem of practice is to determine student achievement in AP Physics C: Mechanics and Electricity and Magnetism when implementing Modeling Instruction. Practice exams from 2015 for AP Physics C: Mechanics and Electricity and Magnetism, FCI, MBT, and BEMA are used to collect data on student achievement in the one-group pretest-posttest method, and the 2017 AP Physics C: Mechanics and Electricity and Magnetism exams are used in the one-shot case study method. The research site is a large high school in a relatively affluent area of the southeast United States, and the high school has received support from the community for many years. Ethical consideration must be taken by the researcher during action research to ensure the students are not harmed, and the highest ethics must be upheld during the implementation, analysis, and reporting of the study.

REFERENCES

American Modeling Teachers Association. (2015a). Curriculum repository. Retrieved from http://modelinginstruction.org/teachers/resources/

American Modeling Teachers Association. (2015b). Home. Retrieved from http://modelinginstruction.org/

Arseneault, M. (2014). *The effects of modeling instruction in a high school physics classroom* (Unpublished master's thesis). Louisiana State University, Baton Rouge, Louisiana.

Beichner, R. (2009). An introduction to physics education research. In C. Henderson & K. Harper (Eds.), *Getting started in PER*. Retrieved from http://www.per-central.org/items/detail.cfm?ID=8806

Brewe, E. (2002). *Inclusion of the energy thread in the introductory physics curriculum: An example of long-term conceptual and thematic coherence* (Doctoral dissertation, Arizona State University). Retrieved from http://modeling.asu.edu/modeling/EricBrewe_Dissertation.pdf

Brewe, E. (2008). Modeling theory applied: Modeling instruction in introductory physics. *American Journal of Physics, 76*(12), 1155-1160. doi: 10.1119/1.2983148.

Brewe, E., Sawtelle, V., Kramer, L. H., O'Brien, G. E., Rodriguez, I., & Pamelá, P. (2010). Toward equity through participation in Modeling Instruction in introductory university physics. *Physical Review Special Topics – Physics Education Research, 6*, 1-12. doi: 10.1103/PhysRevSTPER.6.010106

Bybee, R. (2010). *The teaching of science: 21st century perspectives*. Arlington, Virginia: NSTA Press.

College Board. (2014). AP physics C course description. Retrieved from https://secure-media.collegeboard.org/digitalServices/pdf/ap/ap-physics-c-course-description.pdf

College Board. (2016). AP physics C: Mechanics course home page. Retrieved from http://apcentral.collegeboard.com/apc/public/courses/teachers_corner/2264.html?excmpid=MTG243-PR-34-cd

Dana, N., & Yendol-Hoppey, D. (2014). *The reflective educator's guide to classroom research: Learning to teach and teaching to learn through practitioner inquiry* (3rd ed.). Thousand Oaks, California: Corwin.

Dewey, J. (1910). Science as subject-matter and as method. *Science* 31: 121-127.

Ding, L., Chabay, R., Sherwood, B., & Beichner, R. (2006). Evaluating an electricity and magnetism assessment tool: Brief electricity and magnetism assessment. *Physical Review Special Topics – Physics Education Research,* 2: 1-7. doi: 10.1103/PhysRevSTPER.2.010105.

Haber-Schaim, U. (2006). PSSC physics: A personal perspective. Retrieved from http://www.compadre.org/portal/pssc/docs/Haber-Schaim.pdf

Hake, R. (1998). Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses. *American Journal of Physics*, *66*(1), 64-74. doi: 10.1119/1.18809.

Hestenes, D. (1987). Toward a modeling theory of physics instruction. *American Journal of Physics*, *55*(5), 440-454.

Hestenes, D., Wells, M. (1992). A mechanics baseline test. *The Physics Teacher*, *30*, 141-158.

Hestenes, D., Wells, M., & Swackhamer, G. (1992). Force concept inventory. *The Physics Teacher*, *30*, 141-158.

Hestenes, D. (2006). Notes for a modeling theory of science, cognition and instruction. *Proceedings of the 2006 GIREP Conference*.

Hestenes, D. (2010). Modeling theory for math and science education. In R. Lesh, P. Galbraith, C. Haines, & A. Hurford (Eds.), *Modeling students' mathematical modeling competencies* (pp. 13-41). doi: 10.1007/978-1-4419-0561-1

Hestenes, D. (2015). A role for physicists in STEM education reform. *American Journal of Physics, 83*(2), 101-103. doi:10.1119/1.4904763

Jackson, J., Dukerich, L., & Hestenes, D. (2008). Modeling instruction: An effective model for science education. *Science Educator, 17*(1), 10-17.

Jones, G. & Brader-Araje, L. (2002). The impact of constructivism on education: Language, discourse, and meaning. *American Communication Journal*, *5*(3), 1-10.

Kanselaar, G. (2002). Constructivism and socio-constructivism. Retrieved from http://www.unhas.ac.id/hasbi/LKPP/Hasbi-KBK-SOFTSKILL-UNISTAFF-SCL/Mental%20Model/Constructivism-gk.pdf

Karplus, R. (1969). Three guidelines for elementary school science. *Curriculum Theory Network, 4*, 4-10. Retrieved from http://www.jstor.org/stable/1179305

Melendez, J. & Wirth, D. (2001). *Closing the achievement gap by integrating 9th grade algebra and physics using modeling instruction*. Unpublished manuscript. Retrieved from http://modeling.asu.edu/

Mertler, C. (2014). *Action research: Improving schools and empowering educators* (4th ed.). Thousand Oaks, California: Sage Publications.

MIT Libraries. (2012). Physical Science Study Committee, 1956. Retrieved from https://libraries.mit.edu/archives/exhibits/pssc/

National Academy of Sciences. (2012). *A framework for K-12 science education practices, crosscutting concepts, and core ideas*. Washington, D.C.: National Academies Press.

NGSS Lead States. (2013). Next generation science standards: For states, by states. Retrieved from http://www.nextgenscience.org/

O'Brien, M., & Thompson, J. (2009). Effectiveness of ninth-grade physics in Maine: Conceptual understanding. *The Physics Teacher, 47*, 234-239. doi:10.1119/1.3098211

Procedures for Conducting Research in CCSD Schools. (2015). From Charleston County School District. Retrieved from http://www.ccsdschools.com/Academic/AchievementAccountability/AssessmentEvaluation/ReportsStatistics/ResearchProcedures.php

Rudolph, J. (2006). PSSC in historical context: science, national security, and American culture during the Cold War. Retrieved from http://www.compadre.org/portal/pssc/docs/Rudolph.pdf

South Carolina Department of Education. (2014). *South Carolina academic standards and performance indicators for science.* Retrieved from https://ed.sc.gov/scdoe/assets/file/agency/ccr/Standards-Learning/documents/South_Carolina_Academic_Standards_and_Performance_Indicators_for_Science_2014.pdf

Spring, J. (2014). *The American school: a global context*. (9th ed.). New York: McGraw-Hill.

STEM Education. (n.d.). From Google, Inc. Retrieved from https://www.google.com/#q=stem+education

U.S. Department of Education. (n.d.). Mathematics and Science Partnerships. Retrieved from http://www2.ed.gov/programs/mathsci/index.html

U.S. Department of Education. (2014). *Fiscal year 2015 budget and background information*. Retrieved from http://www2.ed.gov/about/overview/budget/budget15/summary/15summary.pdf

Wells, M., Hestenes, D., & Swackhamer, G. (1995). A modeling method for high school physics instruction. *American Journal of Physics, 63*(7), 606-619.

APPENDIX A – SEQUENCE OF MODELS IN AP PHYSICS C

This is the sequence of models in AP Physics C followed by the researcher during the 2016-2017 school year. For detailed information of each model, see Appendix B.

Mechanics:

1. Constant Velocity Particle Model
2. Uniform Acceleration Particle Model
3. Balanced Force Model
4. Impulsive-Force Model
5. Unbalanced Force Model
6. 2-D Motion Model
7. Energy Storage and Transfer Model
8. Central Net Force Model
9. Rotational Model
10. Harmonic Motion Model

Electricity and Magnetism:

1. Electric Field and Force Model
2. Electric Potential Model
3. Magnetic Field Model
4. Resistor Model
5. Capacitor Model
6. Circuit Model

7. Magnetic Force Model

8. Electromagnetism Model

APPENDIX B – OUTLINE OF MODELS IN AP PHYSICS C

Models in AP Physics C

Adapted from AMTA Modeling Curriculum Resources (modelinginstruction.org)

<u>Parts of a Model:</u>

- Properties: What variables can be measured or calculated?
- Representations: How to we represent this model? (Most equations taken from the 2015 AP Physics C Exam—copyright College Board—equation sheet; some equations are results derived from physical situations.)
- Rules of Behavior: How do properties affect each other?

<u>General Sequence of Instruction:</u>

- Sequence follows ideas from:
  - AMTA materials
  - *Matter and Interactions* by Chabay and Sherwood, 4th edition
- Description of terms in sequence:
  - Activity: Any hands-on work by students; methods, representations, and results displayed on whiteboard; may or may not require written product
  - Discussion: Teacher- or student-led presentation of information
  - Practice: Guided or independent work for students to fully develop the model
  - Quiz: Formative assessment designed to give students information about their learning; uses many types of problems

- Review: Guided or independent work for students to summarize the model
- Test: Summative assessment designed to give students information about their learning; uses many types of problems

Assumptions:

- All students have prior physics knowledge either through a previous course or personal study.
- Students are eventually capable of using calculus in their computational thinking; most students are not introduced to differentials until October and integrals until December.
- Multiple models may be combined into "units" of study; Review and test in this situation is given with information in brackets.
- Information in parenthesis beside model name are the objectives from the College Board Objective List ('M' is for Mechanics, 'EM' is for Electricity and Magnetism).

Mechanics

1. Constant Velocity Particle Model (M.A.1.a.1, M.A.1.a.2, M.A.1.b.1, M.A.2.a.1, M.A.2.a.2)
    a. Parts of the Model:
        i. Properties
            1. Position
            2. Path length
            3. Distance

4. Displacement
5. Speed
6. Velocity
7. Time

ii. Representations

1. Linguistic – Written and Verbal
2. Mathematical
   a. $\Delta\vec{x} = x_f - x_i$
   b. $\Delta t = t_f - t_i$
   c. $\vec{v} = \frac{\Delta\vec{x}}{\Delta t}$
3. Graphical
   a. Position versus time
   b. Velocity versus time
4. Diagrammatic
   a. Motion maps

iii. Rules of Behavior

1. Path length the total distance traveled along a path from starting position to ending position.
2. Displacement is straight-line distance between initial and final positions and includes direction.
3. Speed is path length per change in time.
4. Velocity is change in position per change in time.

5. Slope of position versus time graph is velocity.
6. Area between function and time axis on velocity versus time graph is displacement.

b. Sequence

i. Activity – Buggy Motion

ii. Discussion – Motion Maps, Position versus Time Graphs, Velocity versus Time Graphs

iii. Activity – Ultrasonic Motion Detector

iv. Practice – Motion Maps, Position versus Time Graphs, Velocity versus Time Graphs

v. Quiz – Motion Maps, Position versus Time Graphs, Velocity versus Time Graphs

2. Uniform Acceleration Particle Model (M.A.1.a.1, M.A.1.a.2, M.A.1.b.2, M.A.1.c, M.A.2.a.3, M.D.3.b.1, M.D.3.b.2)

a. Parts of the Model:

i. Properties

1. Velocity
2. Time
3. Uniform acceleration
4. Displacement

ii. Representations

1. Linguistic – Written and Verbal

2. Mathematical

    a. $\vec{a} = \frac{\Delta \vec{v}}{\Delta t}$

    b. $v_x = v_{x0} + a_x t$

    c. $x = x_0 + v_{x0} t + \frac{1}{2} a_x t^2$

    d. $v_x^2 = v_{x0}^2 + 2a_x (x - x_0)$

3. Graphical

    a. Velocity versus time

    b. Acceleration versus time

4. Diagrammatic

    a. Motion maps

iii. Rules of Behavior

1. Acceleration is change in velocity per change in time.

2. Slope of a velocity versus time graph is acceleration.

3. Area between function and time axis on acceleration versus time graph is velocity.

b. Sequence

i. Activity – Motion on an Incline

ii. Discussion – Uniform Acceleration

iii. Practice – Position-Time, Velocity-Time, and Acceleration-Time Graphs

iv. Activity – Motion of Objects

v. Practice – Uniform Acceleration

vi. Activity – Personal Picket Fence

vii. [Review – Constant Velocity and Uniform Acceleration]

viii. [Test – Constant Velocity and Uniform Acceleration]

3. Balanced Force Model (M.B.1, M.B.2.b.2, M.B.3.a, M.B.3.b, M.B.3.c)

    a. Parts of the Model:

        i. Properties

            1. Force

            2. Net force

        ii. Representations

            1. Linguistic – Written and Verbal

            2. Mathematical

                a. $\sum \vec{F} = \vec{F}_{net} = 0$

            3. Graphical

            4. Diagrammatic

                a. Force diagram

                b. Free-body diagram

        iii. Rules of Behavior

            1. Forces are interactions between two objects.

            2. Forces can be classified as either contact or non-contact.

            3. From changes in velocity, we infer forces.

            4. From forces, we deduce changes in velocity.

5. Objects acted upon by balanced forces will not accelerate; instead, they remain at constant velocity.
6. Forces come in pairs; paired forces are equal in magnitude but opposite in direction.

b. Sequence

i. Activity – Bowling Ball Motion
ii. Discussion – Force Diagrams
iii. Practice – Force Diagrams
iv. Practice – Force Calculations
v. Quiz – Force Diagrams and Calculations

4. Impulsive Force Model (M.B.1, M.B.2.a.1, M.B.2.a.2, M.B.2.a.3, M.D.2.a, M.D.2.b, M.D.2.d, M.D.2.e, M.D.3.a.1, M.D.3.a.2, M.D.3.a.3, M.D.3.a.4, M.D.3.a.5)

a. Parts of the Model:

i. Properties

1. Mass
2. Velocity
3. Momentum
4. Force
5. Impulse
6. Time

ii. Representations

1. Linguistic – Written and Verbal
2. Mathematical
    a. $\vec{p} = m\vec{v}$
    b. $\vec{F} = \frac{d\vec{p}}{dt}$
    c. $\vec{J} = \int \vec{F} dt = \Delta\vec{p}$
    d. $\vec{p}_{1i} + \vec{p}_{2i} + \cdots = \vec{p}_{1f} + \vec{p}_{2f} + \cdots$
3. Graphical
    a. Force versus time
    b. Velocity versus time
4. Diagrammatic
    a. Conservation of momentum bar graph
    b. Force diagram
    c. Free-body diagram

iii. Rules of Behavior

1. From changes in momentum, we infer forces.
2. From forces, we deduce changes in momentum.
3. Momentum and energy are conserved in elastic collisions.
4. Momentum is conserved but energy is not conserved in inelastic collisions.

b. Sequence

i. Activity – Golf Ball Impulse

ii. Discussion – Impulse-Momentum Theorem

iii. Practice – Impulse-Momentum Theorem

iv. Activity – Conservation of Momentum

v. Discussion – Conservation of Momentum

vi. Practice – Conservation of Momentum

vii. Quiz – Impulse-Momentum and Conservation of Momentum

5. Unbalanced Force Model (M.B.2.c, M.B.2.d.1, M.B.2.d.2, M.B.2.d.3, M.B.2.e.1, M.B.2.e.2, M.B.2.e.3, M.B.2.e.4, M.B.2.e.5)

   a. Parts of the Model:

      i. Properties

         1. Force
         2. Net force
         3. Mass
         4. Acceleration
         5. Spring constant

      ii. Representations

         1. Linguistic – Written and Verbal
         2. Mathematical

            a. $\vec{a} = \frac{\sum \vec{F}}{m} = \frac{\vec{F}_{net}}{m}$

            b. $|\vec{F}_f| \leq \mu |\vec{F}_N|$

            c. $\vec{F}_S = -k\Delta\vec{x}$

         3. Graphical

a. Any combination of net force, mass, and acceleration

b. Force versus position for a spring

4. Diagrammatic

a. Force diagram

b. Free-body diagram

iii. Rules of Behavior

1. Acceleration is directly proportional to net force and inversely proportional to mass.

2. The numerical value for coefficient of friction is determined by the surfaces.

3. Springs are an example of a restoring force, and each spring has a spring constant.

b. Sequence

i. Activity – Elevator Forces

ii. Activity – Modified Atwood's Machine

iii. Discussion – Net Force Implications

iv. Practice – Force Diagrams and Calculations

v. Activity – Friction

vi. Practice – Force Diagrams and Calculations

vii. Quiz – Force Diagrams and Calculations

viii. Activity – Balloon Rockets

ix. [Review – Balanced Force, Impulsive-Force, and Unbalanced Force]

x. [Test – Balanced Force, Impulsive-Force, and Unbalanced Force]

6. 2-D Motion Model (M.A.2.b, M.A.2.c.1, M.A.2.c.2)

   a. Parts of the Model:

      i. Properties

         1. Position
         2. Displacement
         3. Velocity
         4. Acceleration
         5. Time

      ii. Representations

         1. Linguistic – Written and Verbal
         2. Mathematical

            a. $x = x_0 + v_{x0}t + \frac{1}{2}a_x t^2$

            b. $v_x^2 = v_{x0}^2 + 2a_x(x - x_0)$

            c. $y = y_0 + v_{y0}t + \frac{1}{2}a_g t^2$

            d. $v_y^2 = v_{y0}^2 + 2a_g(y - y_0)$

         3. Graphical

            a. Velocity versus time

            b. Acceleration versus time

4. Diagrammatic
    a. Motion map
iii. Rules of Behavior
    1. A projectile moves both horizontally and vertically and traces a parabolic path in the absence of air resistance.
    2. Horizontal and vertical motion of projectile are independent.

b. Sequence
    i. Activity – Projectiles
    ii. Discussion – 2-D Motion
    iii. Practice – 2-D Motion
    iv. Quiz – 2-D Motion

7. Energy Storage and Transfer Model (M.C.1.a.1, M.C.1.a.2, M.C.1.a.3, M.C.1.a.4, M.C.1.b.1, M.C.1.b.2, M.C.1.b.3, M.C.2.a.1, M.C.2.a.2, M.C.2.b.1, M.C.2.b.2, M.C.2.b.3, M.C.2.b.4, M.C.2.b.5, M.C.3.a.1, M.C.3.a.2, M.C.3.a.3, M.C.3.b.1, M.C.3.b.2, M.C.3.b.3, M.C.3.b.4, M.C.3.c, M.C.4.a, M.C.4.b, M.F.4.a, M.F.4.b, M.F.4.c)
    a. Parts of the Model:
        i. Properties
            1. Energy
            2. Work
            3. Force

4. Displacement
5. Kinetic energy
6. Mass
7. Velocity
8. Gravitational potential energy
9. Spring potential energy
10. Power

ii. Representations

1. Linguistic – Written and Verbal
2. Mathematical
   a. $\Delta E = W = \int \vec{F} \cdot d\vec{r}$
   b. $K = \frac{1}{2} m v^2$
   c. $\left|\vec{F}_G\right| = \frac{G m_1 m_2}{r^2}$
   d. $U_G = -\frac{G m_1 m_2}{r}$
   e. $\Delta U_g = m g \Delta h$
   f. $U_S = \frac{1}{2} k (\Delta x)^2$
   g. $P = \frac{dE}{dt}$
   h. $P = \vec{F} \cdot \vec{v}$
3. Graphical
   a. Force versus displacement
   b. Gravitational potential energy versus displacement

c. Spring potential energy versus displacement

4. Diagrammatic

    a. Force diagram

    b. Energy bar graphs (LOL diagrams)

iii. Rules of Behavior

1. Energy is not disembodied; it is either stored in an object or by a field.
2. Kinetic energy is the energy stored by a moving object.
3. Elastic energy is stored in a deformable body.
4. Magnitude of potential energy depends on the strength of the field and arrangement of objects in the field.
5. Thermal energy includes the kinetic energy associated with the random motion of particles and the potential energy associated with stretching, compressing, and bending the bonds among objects in a system.
6. Energy can be transferred between a system and the surroundings by working, heating, or radiating.
7. Power is the rate of energy transfer.

b. Sequence

i. Activity – Hooke's Law

ii. Discussion – Energy Storage

iii. Activity – Elastic Energy to Kinetic Energy

iv. Activity – Elastic Energy to Gravitational Energy

v. Discussion – Energy Transfer

vi. Practice – Energy Transfer

vii. Quiz – Energy Transfer

viii. Activity – Power

ix. Practice – Power and Energy Transfer

x. [Review – 2-D Motion and Energy Storage and Transfer]

xi. [Test – 2-D Motion and Energy Storage and Transfer]

8. Central Net Force Model (M.E.1.a, M.E.1.b, M.E.1.c, M.E.1.d.1, M.E.1.d.2, M.F.5.a.1, M.F.5.a.2, M.F.5.a.3, M.F.5.b.1, M.F.5.b.2, M.F.5.b.3, M.F.5.b.4)

    a. Parts of the Model:

        i. Properties

            1. Period
            2. Frequency
            3. Velocity
            4. Angular velocity
            5. Centripetal acceleration
            6. Radius
            7. Centripetal force

        ii. Representations

            1. Linguistic – Written and Verbal
            2. Mathematical

a. $a_c = \frac{v^2}{r} = \omega^2 r$

b. $v = r\omega$

c. $T = \frac{2\pi}{\omega} = \frac{1}{f}$

d. $F_c = \frac{mv^2}{r}$

3. Graphical

   a. Any combination of force, velocity, and radius

4. Diagrammatic

   a. Force diagram

   b. Motion map

iii. Rules of Behavior

1. The period of an object in circular motion is the time needed to make one complete rotation.
2. As an object travels in a curved path, the direction of the velocity changes.
3. Acceleration (centripetal) from the velocity change in direction points toward the center of the circle.
4. Force diagrams for an object undergoing circular motion show a net force directed toward the center of the circle.

b. Sequence

i. Activity – Circular Motion

ii. Discussion – Circular Motion

iii. Practice – Circular Motion

iv. Activity – Flying Toys

v. Discussion – Orbits

vi. Practice – Orbits

vii. Quiz – Circular Motion

9. Rotational Motion Model (M.D.1.a.1, M.D.1.a.2, M.D.1.a.3, M.D.1.b, M.D.1.c, M.E.2.a.1, M.E.2.a.2, M.E.2.b.1, M.E.2.b.2, M.E.2.c.1, M.E.2.c.2, M.E.2.d.1, M.E.2.d.2, M.E.2.d.3, M.E.3.a, M.E.3.b, M.E.3.c.1, M.E.3.c.2, M.E.3.c.3, M.E.3.c.4, M.E.3.c.5, M.E.3.d.1, M.E.3.d.2, M.E.3.d.3, M.E.4.a.1, M.E.4.a.2, M.E.4.a.3, M.E.4.b.1, M.E.4.b.2, M.E.4.b.3, M.E.4.b.4)

a. Parts of the Model:

i. Properties

1. Angular velocity
2. Angular acceleration
3. Time
4. Angle
5. Torque
6. Radius
7. Force
8. Moment of inertia
9. Center of mass
10. Angular momentum

ii. Representations

1. Linguistic – Written and Verbal
2. Mathematical
    a. $\omega = \omega_0 + \alpha t$
    b. $\theta = \theta_0 + \omega_0 t + \frac{1}{2}\alpha t^2$
    c. $\vec{\tau} = \vec{r} \times \vec{F}$
    d. $\vec{\alpha} = \frac{\sum \vec{\tau}}{I} = \frac{\vec{\tau}_{net}}{I}$
    e. $I = \int r^2 dm = \sum m r^2$
    f. $x_{cm} = \frac{\sum m_i x_i}{\sum m_i}$
    g. $\vec{L} = \vec{r} \times \vec{p} = I\vec{\omega}$
    h. $K = \frac{1}{2} I \omega^2$
3. Graphical
    a. Angular momentum versus angular velocity
    b. Net torque versus angular acceleration
    c. Kinetic energy versus angular velocity
4. Diagrammatic
    a. Force diagram

iii. Rules of Behavior

1. Angular displacement, velocity, and acceleration may be used to calculate information for objects in rotational motion.

2. The torque an object experiences is related to where and how forces are applied.
3. Moment of inertia of an object is related to the shape and orientation of the object.
4. Angular momentum of an object is related to the moment of inertia and angular velocity of the object.
5. Total kinetic energy of an object is the sum of translational kinetic energy and rotational kinetic energy.
6. Every object has a center of mass, but this point may not be in the geometric middle of the object.

b. Sequence

i. Activity – Levers Simulation
ii. Activity – Torque
iii. Discussion – Angular Motion and Torque
iv. Practice – Angular Motion and Torque
v. Quiz – Angular Motion and Torque
vi. Activity – Rotational Inertia
vii. Discussion – Center of Mass, Angular Momentum, and Energy
viii. Practice – Center of Mass, Angular Momentum, and Energy
ix. Quiz – Center of Mass, Angular Momentum, and Energy
x. Activity – Rolling/Sliding Objects
xi. Discussion – Rolling/Sliding Objects

xii. Practice – Rolling/Sliding Objects

xiii. [Review – Central Net Force and Rotational Motion]

xiv. [Test – Central Net Force and Rotational Motion]

10. Harmonic Motion Model (M.F.1.a, M.F.1.b, M.F.1.c, M.F.1.d, M.F.1.e, M.F.1.f, M.F.1.g, M.F.1.h, M.F.1.i, M.F.1.j, M.F.2.a, M.F.2.b, M.F.2.c, M.F.2.d, M.F.2.e, M.F.3.a, M.F.3.b, M.F.3.c, M.F.3.d)

    a. Parts of the Model:

        i. Properties

            1. Position
            2. Angular velocity
            3. Time
            4. Phase angle
            5. Period
            6. Mass
            7. Spring constant
            8. Length

        ii. Representations

            1. Linguistic – Written and Verbal
            2. Mathematical

                a. $x = x_{max} \cos(\omega t + \varphi)$

                b. $T_S = 2\pi\sqrt{\frac{m}{k}}$

c. $T_p = 2\pi\sqrt{\frac{l}{g}}$

3. Graphical

   a. Position versus time

4. Diagrammatic

   a. Force diagram

iii. Rules of Behavior

1. Plot of position versus time for ideal mass-spring or pendulum system follows repeating function (either sine or cosine).
2. Period for a mass-spring system depends on mass and spring constant.
3. Period for a pendulum depends on length and acceleration due to gravity.

b. Sequence

i. Activity – Horizontal Mass-Spring

ii. Discussion – Oscillations

iii. Activity – Vertical Mass-Spring

iv. Activity – Simple Pendulum

v. Discussion – Simple Pendulum

vi. Practice – Oscillations

vii. Activity – Physical Pendulum

viii. Review – Harmonic Motion

ix. Test – Harmonic Motion

Electricity and Magnetism

1. Electric Field and Force Model (EM.A.1.a.1, EM.A.1.a.2, EM.A.1.b.1, EM.A.1.b.2, EM.A.2.a.1, EM.A.2.a.2, EM.A.2.a.3, EM.A.2.a.4, EM.A.2.a.5, EM.A.2.a.6, EM.A.4.a.1, EM.A.4.a.2, EM.A.4.a.3, EM.A.4.b.1, EM.A.4.b.2.a, EM.A.4.b.2.b, EM.A.4.b.3, EM.A.4.b.4, EM.B.1.a.1, EM.B.1.a.2, EM.B.1.a.3, EM.B.1.b, EM.B.1.c.1, EM.B.1.c.2, EM.B.1.c.3, EM.B.1.c.4)
   a. Parts of the Model:
      i. Properties
         1. Electric charge
         2. Electric force
         3. Electric field
         4. Radius or distance
         5. Vacuum permittivity
      ii. Representations
         1. Linguistic – Written and Verbal
         2. Mathematical
            a. $\left|\vec{F}_e\right| = \frac{1}{4\pi\epsilon_0}\left|\frac{q_1 q_2}{r^2}\right|$
            b. $\vec{E} = \frac{\vec{F}_e}{q}$
            c. $\vec{E} = \frac{1}{4\pi\epsilon_0}\frac{q_1}{|\vec{r}|^2}\hat{r}$

3. Graphical
    a. Force versus distance
    b. Electric field versus position (inside/outside a conductor)
4. Diagrammatic
    a. Force diagram
    b. Electric fields of point charges
    c. Electric fields of continuous charge distributions

iii. Rules of Behavior
1. All matter is composed of charged particles, with varying charge mobility in different materials.
2. Like charges repel but opposite charges attract.
3. Neutral matter may be polarized.
4. Electric force is dependent on charges and distance.
5. The electric field vector points in the same direction as the electric force vector.

b. Sequence

i. Activity – Sticky Tape

ii. Discussion – Electrostatics

iii. Practice – Coulomb's Law

iv. Activity – Electric Field Hockey

v. Discussion – Electric Fields

vi. Activity – Electric Fields

vii. Practice – Electric Fields

viii. Quiz – Electric Forces and Fields

ix. Discussion – Electric Fields of Charge Distributions

x. Practice – Electric Fields of Charge Distributions

xi. Quiz – Electric Fields of Charge Distributions

xii. Review – Electric Forces and Fields

xiii. Test – Electric Forces and Fields

2. Electric Potential Model (EM.A.2.b.1, EM.A.2.b.2, EM.A.2.b.3, EM.A.2.b.4, EM.A.2.b.5, EM.A.2.b.6, EM.A.2.b.7, EM.A.2.b.8)

    a. Parts of the Model:

        i. Properties

            1. Electric field

            2. Electric potential energy

            3. Electric potential

            4. Path length

            5. Radius

            6. Vacuum permittivity

        ii. Representations

            1. Linguistic – Written and Verbal

            2. Mathematical

                a. $E_x = -\frac{dV}{dx}$

b. $\Delta V = -\int \vec{E} \cdot d\vec{r}$

c. $V = \frac{1}{4\pi\varepsilon_0} \sum_i \frac{q_i}{r_i}$

d. $U_E = qV = \frac{1}{4\pi\varepsilon_0} \frac{q_1 q_2}{r}$

3. Graphical

    a. Electric potential versus position (inside/outside a conductor)

4. Diagrammatic

    a. Equipotentials for point charges

    b. Equipotentials for continuous charge distributions

iii. Rules of Behavior

1. Electric potential is a property of location, not a material.
2. Motion parallel to electric field lines does not have a change in energy; motion non-parallel to electric field lines does have a change in energy.
3. Electric potential energy is difficult to measure, so instead we typically measure electric potential.

b. Sequence

i. Activity – Voltaic Piles

ii. Discussion – Electric Potential Energy and Electric Potential

iii. Practice – Equipotentials

iv. Practice – Electric Potential Energy and Electric Potential

v. Quiz – Electric Potential

3. Magnetic Field Model (EM.D.3.a, EM.D.3.b, EM.D.3.c, EM.D.4.a.1, EM.D.4.a.2, EM.D.4.c)
    a. Parts of the Model:
        i. Properties
            1. Magnetic field
            2. Current
            3. Charge
            4. Radius
            5. Vacuum permeability
            6. Inductance
            7. Magnetic potential energy
        ii. Representations
            1. Linguistic – Written and Verbal
            2. Mathematical
                a. $I = \frac{dQ}{dt}$
                b. $\vec{B} = \frac{\mu_0}{4\pi}\frac{q\vec{v}\times\hat{r}}{r^2}$
                c. $d\vec{B} = \frac{\mu_0}{4\pi}\frac{Id\vec{l}\times\hat{r}}{r^2}$
                d. $B_S = \mu_0 nI$
                e. $U_L = \frac{1}{2}LI^2$
            3. Graphical

a. Magnetic field versus position

4. Diagrammatic

   a. Magnetic fields of bar magnets

   b. Magnetic fields of short piece of current-carrying wire

   c. Magnetic fields of continuous current distributions

iii. Rules of Behavior

1. Magnetic fields originate from charge motion.

2. Field strength diminishes with distance from moving charge and increases with increasing charge motion.

3. Fields are loops and can be described with the right-hand rule.

4. Energy can be stored as a magnetic field in a solenoid.

b. Sequence

i. Activity – Oersted

ii. Discussion – Electron Current

iii. Discussion – Magnetic Fields

iv. Practice – Magnetism

v. Discussion – Magnetic Fields of Current Distributions

vi. Practice – Magnetic Fields

vii. Quiz – Magnetic Fields

viii. [Review – Electric Potential and Magnetic Fields]

ix. [Test – Electric Potential and Magnetic Fields]

4. Resistor Model (EM.C.1.a, EM.C.1.b.1, EM.C.1.b.2, EM.C.1.b.3, EM.C.1.b.4, EM.C.1.b.5, EM.C.1.b.6)
    a. Parts of the Model:
        i. Properties
            1. Resistance
            2. Resistivity
            3. Length
            4. Current density
            5. Number of charge carriers per unit volume
            6. Drift velocity
            7. Current
        ii. Representations
            1. Linguistic – Written and Verbal
            2. Mathematical
                a. $I = \frac{dQ}{dt}$
                b. $R = \frac{\rho l}{A}$
                c. $\vec{E} = \rho\vec{J}$
                d. $I = Nev_d A$
                e. $R_s = \sum_i R_i$
                f. $\frac{1}{R_p} = \sum_i \frac{1}{R_i}$

3. Graphical
    a. Any combination of resistivity, length, and area
4. Diagrammatic
    a. Representation of charge carriers in resistor

iii. Rules of Behavior
1. Resistance is the net effect of atomic level 'obstacles' interfering with the motion of charge carriers.
2. Resistance is directly proportional to resistivity of the material and length, and inversely proportional to cross-sectional area.
3. Resistance adds when resistors are connected in series, and reduces when resistors are connected in parallel.

b. Sequence
i. Activity – What is happening in the wires?
ii. Discussion – Fields and Potential Differences in Circuits
iii. Discussion – Surface Charge Distributions
iv. Activity – Resistivity of Play-Doh
v. Discussion – Resistance
vi. Practice – Resistance

5. Capacitor Model (EM.B.2.a.1, EM.B.2.a.2, EM.B.2.a.3, EM.B.2.b.1, EM.B.2.b.2, EM.B.2.b.3, EM.B.2.b.4, EM.B.2.b.5, EM.B.2.b.6, EM.B.2.c.1, EM.B.2.c.2, EM.B.3.a, EM.B.3.b)

a. Parts of the Model:

   i. Properties

      1. Electric potential
      2. Charge
      3. Capacitance
      4. Dielectric constant
      5. Vacuum permittivity
      6. Area
      7. Separation distance
      8. Electric potential energy

   ii. Representations

      1. Linguistic – Written and Verbal
      2. Mathematical

         a. $\Delta V = \frac{Q}{C}$
         b. $C = \frac{\kappa \varepsilon_{0A}}{d}$
         c. $C_p = \sum_i C_i$
         d. $\frac{1}{C_s} = \sum_i \frac{1}{C_i}$
         e. $U_C = \frac{1}{2} Q \Delta V = \frac{1}{2} C(\Delta V)^2$

      3. Graphical

         a. Any combination of capacitance, area, and separation distance

4. Diagrammatic

    a. Equivalent capacitance schematics

iii. Rules of Behavior

1. Creating an uneven distribution of charge produces an electric field and electric potential difference between two locations.
2. Capacitance adds when capacitors are connected in parallel, and reduces when capacitors are connected in series.
3. Capacitance is directly proportional to the dielectric constant and surface area, and inversely proportional to plate separation distance.

b. Sequence

i. Activity – Capacitance of Parallel Plates

ii. Discussion – Capacitance

iii. Practice – Capacitance

6. Circuit Model (EM.C.2.a.1, EM.C.2.a.2, EM.C.2.a.3, EM.C.2.a.4, EM.C.2.a.5, EM.C.2.b.1, EM.C.2.b.2, EM.C.2.c.1, EM.C.2.c.2, EM.C.2.d.1, EM.C.2.d.2, EM.C.2.d.3, EM.C.3.a.1, EM.C.3.a.2, EM.C.3.a.3, EM.C.3.a.4, EM.C.3.b.1, EM.C.3.b.2, EM.C.3.b.3, EM.C.3.b.4)

a. Parts of the Model:

i. Properties

1. Electric potential

2. Current
3. Resistance
4. Capacitance
5. Power
6. Charge

ii. Representations

1. Linguistic – Written and Verbal
2. Mathematical
   a. $I = \frac{\Delta V}{R}$
   b. $P = I\Delta V$
   c. $I = I_0 e^{-t/RC}$
   d. $Q = CV(1 - e^{-t/RC})$
   e. $Q = Q_0 e^{-t/RC}$
3. Graphical
   a. Any combination of current, electric potential, and resistance
   b. Current versus time for charging/discharging RC circuit
   c. Voltage versus time for charging/discharging RC circuit
   d. Charge versus time for charging circuit

e. Charge versus time for discharging circuit

4. Diagrammatic

a. Resistor-only circuit schematics

b. Resistor-capacitor circuit schematics

iii. Rules of Behavior

1. A conducting path allows constrained charge motion between the points as long as the uneven charge distribution is maintained.

2. When there is more than one pathway for current to travel, the total current into the junction is equal to the total current leaving the junction.

3. The voltage gains and drops around a closed loop of a circuit is equal to zero.

4. The rate at which charge accumulates on a capacitor or current flows in a RC circuit depends on the resistance and capacitance.

b. Sequence

i. Activity – Circuits (Resistor-Only)

ii. Discussion – Circuits (Resistor-Only)

iii. Practice – Circuits (Resistor-Only)

iv. Discussion – Kirchhoff's Rules

v. Practice – Kirchhoff's Rules

vi. Quiz – Circuits (Resistor-Only)

vii. Activity – RC Circuits

viii. Discussion – RC Circuits

ix. Practice – RC Circuits

x. Quiz – RC Circuits

xi. [Review – Resistance, Capacitance, Circuits]

xii. [Test – Resistance, Capacitance, Circuits]

7. Magnetic Force Model (EM.D.1.a, EM.D.1.b, EM.D.1.c, EM.D.1.d, EM.D.1.e, EM.D.2.a, EM.D.2.b, EM.D.2.c)

    a. Parts of the Model:

        i. Properties

            1. Charge
            2. Magnetic field
            3. Magnetic force
            4. Magnetic potential energy
            5. Magnetic dipole
            6. Electromotive force (Emf)
            7. Number of turns per unit length

        ii. Representations

            1. Linguistic – Written and Verbal
            2. Mathematical

                a. $\vec{F}_M = q\vec{v}\times\vec{B}$

b. $\vec{F} = \int I \, d\vec{l} \times \vec{B}$

c. $\vec{\tau} = \vec{\mu} \times \vec{B}$

d. $|\vec{\mu}| = nIA$

3. Graphical

    a. Any combination of magnetic force, velocity or current, and magnetic field

    b. Magnetic potential energy and current

4. Diagrammatic

    a. Free-body diagram

    b. Magnetic field of a solenoid

iii. Rules of Behavior

1. Force is exerted on a charge moving in a magnetic field.
2. Directions of force, charge/current, and magnetic field can be found with the right-hand rule.
3. A current-carrying coil or magnetic dipole experiences torque in a magnetic field and twists to align with the applied magnetic field.

b. Sequence

i. Activity – Magnetic Fields of Current-Carrying Wire, Solenoid, and Magnets

ii. Discussion – Magnetic Force on Moving Charge and Current-Carrying Wire

iii. Practice – Magnetic Force on Moving Charge and Current-Carrying Wire
iv. Discussion – Electric and Magnetic Forces
v. Practice – Magnetic Force
vi. Quiz – Magnetic Force
vii. Discussion – Motional Emf
viii. Discussion – Torque from Magnetic Forces
ix. Practice – Motional Emf
x. Activity – Motors and Generators
xi. Practice – Torque, Motors, and Generators
xii. Review – Magnetic Force
xiii. Test – Magnetic Force

8. Electromagnetism Model (EM.A.3.a.1, EM.A.3.a.2, EM.A.3.a.3, EM.A.3.b.1, EM.A.3.b.2, EM.A.3.b.3, EM.D.4.b.1, EM.D.4.b.2, EM.E.1.a.1, EM.E.1.a.2, EM.E.1.b.1, EM.E.1.b.2.a, EM.E.1.b.2.b, EM.E.1.b.2.c, EM.E.2.a.1, EM.E.2.a.2, EM.E.2.b.1, EM.E.2.b.2, EM.E.2.b.3, EM.E.2.b.4, EM.E.2.b.5, EM.E.2.b.6, EM.E.3)
    a. Parts of the Model:
        i. Properties
            1. Electric field
            2. Area
            3. Charge

4. Vacuum permittivity
5. Magnetic field
6. Length
7. Vacuum permeability
8. Electric flux
9. Magnetic flux
10. Emf
11. Time
12. Inductance
13. Current
14. Force

ii. Representations

1. Linguistic – Written and Verbal
2. Mathematical
    a. $\oint \vec{E} \cdot d\vec{A} = \frac{Q}{\varepsilon_0}$
    b. $\oint \vec{B} \cdot d\vec{l} = \mu_0 I$
    c. $\Phi_B = \int \vec{B} \cdot d\vec{A}$
    d. $\varepsilon = \oint \vec{E} \cdot d\vec{l} = -\frac{d\Phi_B}{dt}$
    e. $\varepsilon = -L\frac{dI}{dt}$
    f. $\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$
3. Graphical

a. Induced emf versus change in magnetic flux per time
b. Induced emf versus current

4. Diagrammatic
   a. Force diagram
   b. Gaussian surface
   c. Amperian loop

iii. Rules of Behavior

1. Electric flux is the quantitative measure of the amount and direction of electric field over an entire surface.
2. Gaussian surfaces can be used to determine values associated with electric fields and charge distributions.
3. Magnetic flux is the quantitative measure of the amount and direction of magnetic field over an entire surface.
4. Amperian loops can be used to determine values associated with magnetic fields and current distributions.
5. Induced emf is related to the inductance and change in current, or the change in magnetic flux.
6. The total force on a moving charged particle is the sum of the electric force and magnetic force.

b. Sequence

i. Activity – Electromagnets

ii. Discussion – Gauss’s Law and Ampere’s Law
iii. Practice – Gauss’s Law and Ampere’s Law
iv. Activity – RL Circuits
v. Discussion – Faraday’s Law and Motional Emf
vi. Practice – Faraday’s Law and Motional Emf
vii. Discussion – Maxwell’s Equations
viii. Discussion – Inductance
ix. Practice – Inductance and RL Circuits
x. Review – Electromagnetism
xi. Test – Electromagnetism

APPENDIX C – CONSENT LETTER

Dear Students, Parents, and Guardians,

This is my fifth year teaching physics, and each year I strive to be better at my craft. To do this, I am enrolled in the Doctor of Education (Ed.D.) in Curriculum and Instruction program at the University of South Carolina. I have taken classes for the last several years, and it is time to complete my dissertation research for the doctoral program.

The University of South Carolina utilizes an action research model for their Ed.D. program, which means that I chose something I think I could do better in my teaching and perform a research study on that topic. My topic is Modeling Instruction, which is a way to teach students collaboration, critical thinking, communication, and creativity through science by organizing scientific principles into models. Students develop, refine, and break their models, justifying their choices through written, verbal, mathematical, graphical, and diagrammatic thinking. I will provide opportunities for students to engage with scientific concepts and guide students to think more deeply and clearly about the way their model represents the concept. Many studies have shown that Modeling Instruction helps to increase student engagement and achievement, and I will have time to differentiate lessons so that the needs of all students are met.

You were selected to participate in this study because you are in my AP Physics C: Mechanics and Electricity and Magnetism courses for 2016-2017. There is no penalty for not participating, and you may withdraw from the study at any time without penalty.

[Redacted] School District and [redacted] High School are neither sponsoring nor conducting this research. Any physical, psychological, legal, or other risks are small; this will be my second year using Modeling Instruction and teaching AP Physics C, so I have an understanding of how to positively implement the strategies. The only person with access to personally identifiable data will be me, and information related to student scores and/or grades will be presented so that no one can identify students. If a particular student is mentioned (in a problem-solving description, for example), I will use a pseudonym so that the student(s) cannot be identified. The results of this study will be published in my dissertation, which will be available on the internet. If any parent/guardian wishes to see materials before providing their consent, I would be happy to meet, discuss the study, and provide the materials.

The study would require approximately 5 hours of class time during the fall semester and approximately 4 hours of class time during the spring semester for all students participating in the study. Quantitative data collection for this study is the following:

- Student grades and/or test scores from prior science and mathematics courses
- Student scores on research-validated instruments on physics content as pretests and posttests
- Student scores from the 2017 AP Physics C: Mechanics and Electricity and Magnetism exams

This information will be analyzed for basic statistical information and to determine the effect of Modeling Instruction on student achievement.

For qualitative data collection, selected students will participate in interviews at four points during the fall semester and an additional four points during the spring semester. These interviews will be conducted either in class during problem-solving time or before/after school and will be approximately 30 minutes in length. This information will be analyzed to determine the effect of Modeling Instruction on the problem-solving ability of students.

Students would benefit from this research by having a better understanding of physics principles and potentially increased scores on the AP Physics C: Mechanics and Electricity and Magnetism exams. The science education community, particularly those interested in Modeling Instruction, would benefit by having a study discussing the use of Modeling Instruction in AP Physics C: Mechanics and Electricity and Magnetism. Currently there are no studies related to this topic, and my research would positively impact the science education research base. [Redacted] School District will benefit from this research because I can share information with other science teachers, highlighting the positive aspects of teaching science with Modeling Instruction.

If there are any questions, comments, or concerns about this study, please contact me at 843.849.2830 extension 27383 or at nathan_belcher@charleston.k12.sc.us. I am in many different classrooms throughout the day, so email is the preferred method of communication.

Sincerely,

Nathan Belcher

Physics (AP, Honors, CP) Teacher at [redacted] High School

Ed.D. Candidate at the University of South Carolina

Student: I, ________________________, agree to participate in this study on Modeling Instruction in AP Physics C. I understand that I may opt out of the study at any time without penalty.

Signature: __________________________________ Date: _____________

Parent/Guardian: The student named above has my permission to participate in this test of a study and learning method.

Signature: __________________________________ Date: _____________

Parent/Guardian: I do NOT wish for my student to participate.

Signature: __________________________________ Date: _____________

APPENDIX D – PERMISSION TO USE INFORMATION

The researcher received permission to use figures 2.1, 2.2, 2.3, and 2.4 and table 2.1 from Dr. David Hestenes via email communication on October 10, 2015.

The researcher received permission from The College Board AP Permissions to use student scores on the 2015 AP Physics C: Mechanics and Electricity and Magnetism Practice Exams via email communication on August 15, 2016. The researcher agreed not to use any information related to specific questions or reproduce specific questions, and the analysis will be performed with aggregate student scores.