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

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DEDICATION

This dissertation is dedicated to every teacher who pushes themselves to improve. You are helping the next generation learn, which is the foundation of our humanity.

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ABSTRACT

This action research study used data from multiple assessments in Mechanics and Electricity and Magnetism to determine the viability of Modeling Instruction as a pedagogy for students in AP Physics C: Mechanics and Electricity and Magnetism. Modeling Instruction is a guided-inquiry approach to teaching science in which students progress through the Modeling Cycle to develop a fully-constructed model for a scientific concept. AP Physics C: Mechanics and Electricity and Magnetism are calculus-based physics courses, approximately equivalent to first-year calculus-based physics courses at the collegiate level. Using a one-group pretest-posttest design, students were assessed in Mechanics using the Force Concept Inventory, Mechanics Baseline Test, and 2015 AP Physics C: Mechanics Practice Exam. With the same design, students were assessed in Electricity and Magnetism on the Brief Electricity and Magnetism Assessment, Electricity and Magnetism Conceptual Assessment, and 2015 AP Physics C: Electricity and Magnetism Practice Exam. In a one-shot case study design, student scores were collected from the 2017 AP Physics C: Mechanics and Electricity and Magnetism Exams. Students performed moderately well on the assessments in Mechanics and Electricity and Magnetism, demonstrating that Modeling Instruction is a viable pedagogy in AP Physics C: Electricity and Magnetism.

Keywords: Modeling Instruction, AP Physics C, action research

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LIST OF ABBREVIATIONS

AAPT ....American Association of Physics Teachers

AMTA..American Modeling Teachers Association

AP ....Advanced Placement

BEMA ....Brief Electricity and Magnetism Assessment

EM..Electricity and Magnetism

EMCA ....Electricity and Magnetism Conceptual Assessment

FCI ....Force Concept Inventory

MBT..Mechanics Baseline Test

NGSS ....Next Generation Science Standards

NSF ....National Science Foundation

PER .... Physics Education Research

PSSC .... Physical Science Study Committee

SCIS ....Science Curriculum Improvement Study

CHAPTER ONE: Introduction

Science coursework has been included in the K-12 education system throughout the history of education in the United States, though mathematics and science classes gained special prominence in 1957 after the launch of *Sputnik I* by the Soviet Union (Bybee, 2010). Concerned that the United States was trailing the Soviet Union in scientific and technological research, the federal government began pouring large amounts of money into science education to develop the next generation of researchers. Groups of scientists and educators from universities, national science laboratories, and national science professional organizations began to write standards and create curriculum for K-12 science education, developing innovative methods for teaching science. One influential group, the Physical Science Study Committee (PSSC), produced curriculum and instruction that emphasized scientific thinking within the context of specific science content (Bybee, 2010; Haber-Schaim, 2006; MIT Libraries, 2012; Rudolph, 2006). Ideas from the PSSC were expanded in the ensuing decades; in the late 1980s, Dr. David Hestenes, physics professor at Arizona State University, and Dr. Malcolm Wells, high school physics teacher and doctoral student at Arizona State University, created Modeling Instruction (Hestenes, 1987).

A major problem in science education is the organization of content into discrete chunks that are to be memorized and tested; this chunking has been an issue throughout the history of science education. Hestenes and Wells developed Modeling Instruction to expand the ideas of the PSSC by coordinating scientific thinking and science content around models, providing a structure for students' thinking. Each unit of study begins with a laboratory experience to engage students in science content and create an initial conceptual model, then students test and refine the initial conceptual model through problem-solving and further laboratories to create a fully-constructed model. Through the Modeling Cycle—the process of creating and testing a conceptual model—Modeling Instruction becomes a hands-on, student-centered approach to teaching both the process and content of scientific disciplines (Jackson, Dukerich, & Hestenes, 2008).

In addition to developing and refining materials for Modeling Instruction, Hestenes (1987, 2006, 2010, 2015, & 2016) created a Modeling Theory of Cognition. This theory connects constructivism, cognitive psychology, and cognitive linguistics to provide a framework for how humans organize information into personal mental models; when groups of humans compare personal mental models, similar information may be combined into a conceptual model. These conceptual models are used to predict future events; depending on the outcome of the prediction or new observations, anyone may change the conceptual model. The Modeling Theory of Cognition forms the foundation of Modeling Instruction; consistency between a theory of cognition and an instructional approach provides students a greater chance of success in science courses.

This dissertation traces the development of pedagogy in science education, details the Modeling Theory of Cognition, and discusses the implementation of Modeling Instruction within Advanced Placement (AP) Physics C: Mechanics and Electricity and Magnetism courses. I became interested in these topics after partially implementing Modeling Instruction in AP Physics C: Mechanics and Electricity and Magnetism during the 2015-2016 school year; 2015-2016 was my first year teaching AP Physics C:

Mechanics and Electricity and Magnetism. Students were moderately successful in these courses during 2015-2016 on the AP Physics exam. Based on this moderate success, I wondered if a full implementation of Modeling Instruction in AP Physics C: Mechanics and Electricity and Magnetism during the next school year would help students better understand physics and be more successful on the AP exams. To determine if Modeling Instruction is a viable strategy for AP Physics C: Mechanics and Electricity and Magnetism, I performed action research during the 2016-2017 school year. I organized topics in the AP Physics C: Mechanics and Electricity and Magnetism courses into models and Modeling Cycles (see Appendices A, B, and C for further information) and used instructional strategies contained within Modeling Instruction. This dissertation provides evidence of reasonable student performance on research-based assessments and AP exams, leading to the conclusion that Modeling Instruction is a viable pedagogy for teaching students in AP Physics C: Mechanics and Electricity and Magnetism.

Statement of the Problem of Practice

The problem of practice for this dissertation was to determine the viability of Modeling Instruction as a pedagogy for students in AP Physics C: Mechanics and Electricity and Magnetism.

Research Question

This study was guided by the following primary research question: Is Modeling Instruction a viable pedagogy in AP Physics C: Mechanics and Electricity and Magnetism? From student scores on assessments in Mechanics and Electricity and Magnetism, the viability of Modeling Instruction was judged by calculating raw and normalized gains. Higher raw and normalized gains indicate a greater viability for

Modeling Instruction as a pedagogy for students in AP Physics C: Mechanics and Electricity and Magnetism because higher scores indicate that students have a better understanding of the physics concepts. This question is unique within literature pertaining to Modeling Instruction and AP Physics C: Mechanics and Electricity and Magnetism because there are no previously published studies. This dissertation will contribute to theoretical and experimental research in Physics Education Research (PER).

Purpose of the Study

The general purpose of the study was to determine the viability of Modeling Instruction as a pedagogy in AP Physics C: Mechanics and Electricity and Magnetism. Specifically, the chapters in this dissertation will discuss the following:

(a) The development of science education from the late 1800s to the present, showing that the pedagogical practices embedded in Modeling Instruction are the next development in science education;

(b) The connection between constructivism and the Modeling Theory of Cognition;

(c) The connection between Modeling Instruction and modern views of learning;

(d) Data analysis of student scores with basic statistical methods and graphs that describe correlations between assessments;

(e) Results and implications Modeling Instruction is a viable pedagogical method in AP Physics C;

(f) Updating physics models to include information in calculus-based physics and create new models for topics outside the existing set of physics models; and,

(g) Developing a standardized method for describing models.

Methodology

Practitioner-based research is known as action research; this type of research allows the practitioner to analyze their work and make improvements based on the results of the research. One model of action research—developed by Mertler (2014)—consists of four stages: Planning, acting, developing, and reflecting. In the planning stage, the researcher identifies a topic, gathers information, reviews related literature, and develops an initial research plan. In the acting stage, the researcher implements the initial research plan to collect and analyze data. In the developing stage, the researcher generates conclusions from the initial data analysis and modifies the research plan to collect and analyze more data. In the reflecting stage, the researcher draws conclusions from the second data analysis, communicates results, and reflects on the action research process (Mertler, 2014). The cyclical nature of action research gives power to the practitioner because they build from previous research experience to make improvements for an issue, department, or course. This study used action research to develop robust AP Physics C: Mechanics and Electricity and Magnetism courses for my benefit and others who teach AP Physics C: Mechanics and Electricity and Magnetism.

The site for this study was a large, suburban high school in the southeastern United States. In the 2016-2017 school year, the high school had a student body of over 4,100 students; the ethnic composition was 81% Caucasian, 13% African-American, 3% Hispanic, and 3% other ethnicities. Approximately 43% were served by gifted and talented program, 8% were classified as students with disabilities, and 20% were considered “in poverty.” The school provided 28 AP courses; these courses served approximately 41% of the student population, with 81% of students taking an AP course scoring a 3 or higher on the AP exam. With a faculty of 255 teachers offering over 250 courses, the high school received an absolute rating of “Excellent” from the state Department of Education from 2010 to 2016. The school’s clubs and teams achieved a high level of success, driven by dedicated and talented students, teachers, and coaches. Students for this study were selected by enrolling in my AP Physics C: Mechanics and Electricity and Magnetism courses during 2016-2017. There were 20 students in the Mechanics assessment data and 16 students in the Electricity and Magnetism assessment data; the reduced number of students in Electricity and Magnetism stems from students opting out of the study without penalty.

Most studies with Modeling Instruction have used quantitative methods to measure changes in student understanding. Physics education researchers have developed robust multiple-choice assessments that probe for student understanding on many topics; researchers designed these assessments so that higher scores indicate students have a higher understanding of the topics. The problem of practice and research question for this study were designed to determine the viability of Modeling Instruction as a pedagogy by measuring raw and normalized gains of student scores on assessments, so the most appropriate research methods are quantitative. Higher raw and normalized gains suggest that a pedagogy is a more viable method for teaching students about physics, leading to more students to achieve a deeper understanding of physics concepts. This study used several assessments for two quantitative action research designs: A one-group pretest-posttest method and a one-shot case study (Mertler, 2014).

For the one-group pretest-posttest method, student scores were collected on the following assessments:

- 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);
- Electricity and Magnetism Conceptual Assessment (EMCA).

For each assessment, gains were calculated with two methods: The average of the gains and simple subtraction. Simple statistical measures (mean, median, standard deviation, range) were performed on each assessment. Scores were graphed in several ways, highlighting relationships within and between assessments.

In the one-shot case study, scores from the 2017 AP Physics C: Mechanics and Electricity and Magnetism exams were collected. Simple statistical analysis—mean, median, standard deviation, range—was performed on the overall scores from the 2017 AP exams. In addition, a content-specific breakdown of scores provided information on student performance.

Significance of the Study

There are several reasons why this study is significant. Most importantly, this was the first published study that provides information on the viability of Modeling Instruction as a pedagogy in AP Physics C: Mechanics and Electricity and Magnetism. Secondarily, the review of literature in this study helps practitioners understand foundational aspects of Modeling Instruction: Historical influences that led to the creation of Modeling Instruction; connections between learning theory and the Modeling Theory of Cognition; the Modeling Cycle; and, connections between AP Physics C:

Mechanics and Electricity and Magnetism learning objectives and models. Each of these foundational aspects enhanced my implementation of Modeling Instruction, improving student learning in AP Physics C: Mechanics and Electricity and Magnetism.

Limitations or Potential Weaknesses of the Study

Although many positive aspects to this study exist, there are several limitations or potential weaknesses of the study. One limitation is related to the action research design. This study used a one-group pretest-posttest method, which means there was no control group of students at the same research location that could be used as a comparison with the group of students receiving Modeling Instruction. Another limitation to the study is using a one-shot case study with the assessment as the AP Physics C: Mechanics and Electricity and Magnetism exams. If students did not perform well on the AP Physics C: Mechanics and Electricity and Magnetism exams, their score could misrepresent their level of understanding of physics; students could have a variety of reasons for performing better or worse on the AP exams relative to their achievement on other assessments. A potential weakness of the study is that students may enter the course with a high level of physics understanding, reducing the impact of any pedagogical strategy.

Dissertation Overview

The topic, structure, and overall importance of the study has been discussed in Chapter One. This chapter is followed by four additional chapters discussing previous literature, action research methodology, findings from the data analysis, and discussion, implications, and recommendations. Chapter Two is the literature review, which provides an overview of studies related to Modeling Instruction. These works discuss the historical context of science education, situating this research within the science education research community. The Modeling Theory of Cognition provides information related to how humans learn, leading to the development of Modeling Instruction as a viable pedagogy for teaching science. Results of previous Modeling Instruction studies demonstrate the success of this pedagogy at the high school and university levels, including a discussion regarding the impact of Modeling Instruction on students from diverse backgrounds. Chapter Three discusses the action research methodology—including the setting, time frame, and participants for the study—and procedures for data collection and analysis. Chapter Four presents a thorough and systematic analysis of the data sets, discussing findings and interpretations of results of the study. Chapter Five summarizes major points of the study, including an interpretation of results, implications of the results, and suggestions for future research.

Conclusion

The problem of practice for this dissertation was to determine the viability of Modeling Instruction as a pedagogy for students in AP Physics C: Mechanics and Electricity and Magnetism. This study utilized quantitative action research in the form of a one-group pretest-posttest and one-shot case study to evaluate the implementation of Modeling Instruction in AP Physics C: Mechanics and Electricity and Magnetism. Students were assessed in Mechanics and Electricity and Magnetism; scores on these assessments and the AP exams are used to determine the viability of Modeling Instruction on student achievement. The Modeling Theory of Cognition provides ideas about how science should be taught, leading to Modeling Instruction. This instructional approach aligns curriculum, instruction, and assessment with the Modeling Theory of

Cognition, providing a way for students to develop accurate models of the way the world works.

Definition of Terms

Brief Electricity and Magnetism Assessment (BEMA): A 30-item assessment that tests student understanding of electricity and magnetism assessments; developed by Chabay, Sherwood, and Reif; rated a "Gold" assessment by Madsen, McKagan, & Sayre (2017)

Concept: A personal mental model that has been formalized for sharing with others, defined by three parts—symbol, form, and meaning (Hestenes, 2015)

Conceptual model: A model that has been formalized by a group of people, defined by three parts—structure, referent, and representation (Hestenes, 2015)

Constructivism: An epistemological view of knowledge acquisition that emphasizes knowledge construction—the process of building new knowledge structures by synthesizing new information with prior knowledge structures

Electricity and Magnetism Conceptual Assessment (EMCA): A 30-item assessment that tests student understanding of electricity and magnetism assessments; developed by Broder, McColgan, and Finn; rated a "Bronze" assessment by Madsen et al. (2017)

Force Concept Inventory (FCI): 30-item assessment that determines conceptual understanding on the topic of force (Hestenes, Wells, & Swackhamer, 1992); rated a "Gold" assessment by Madsen et al. (2017)

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); rated a “Bronze” assessment by Madsen et al. (2017)

Mental models: Private construction of a narrative in the mind of an individual (Hestenes, 2015)

Model: "A representation of structure in a system of objects” (Hestenes, 2015, slide 15)

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); there are three parts to the Modeling Cycle: Develop an initial model from data and analysis in an introductory laboratory activity; create a fully-constructed model by refining and expanding the model through discussion and further laboratory activities; and, apply the fully-constructed model through written practice, engineering design challenges, or laboratory activities

Modeling Instruction: Combination of the Modeling Theory of Cognition and instructional practices that create a coherent conceptual understanding for students; process by which science is performed and understood (Hestenes, 2015)

Normalized Gain (Average of Gains): A measure of the effectiveness of teaching methods in Physics Education Research; the equation is $g_{ave} = \langle(Posttest\ \% - Pretest\ \%)\ /\ (100\% - Pretest\ \%)\rangle$ (McKagan, Sayre, & Madsen, 2017)

Pedagogy: Method and practice of teaching

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

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; four types are sufficient for a model—systemic, geometric, interaction, and temporal (Hestenes, 2006)

System: A set of related objects, which may be real or imaginary, physical or mental, or simple or composite (Hestenes, 2006)

CHAPTER TWO: Review of Literature

As the amount of scientific understanding and emphasis on science in daily life has increased over the last 150 years, pedagogical techniques have become more sophisticated in science education. Pedagogies that demonstrate the highest levels of student achievement integrate advances in cognitive psychology and learning theory into all aspects of curriculum, instruction, and assessment (Hake, 1998; Hsu, Brewe, Foster, & Harper, 2004; Kohlmyer et al., 2009; Madsen, McKagan, & Sayre, 2015; Rosengrant, Etkina, & Van Heuvelen, 2006; Von Korff, 2016). This integration of cognitive psychology and learning theory leads to a pedagogy with coherent design and function. The Modeling Theory of Cognition (Hestenes, 1987, 2006, 2010, 2015, & 2016) is a theory of learning that connects constructivism, advances in cognitive psychology, and cognitive linguistics to create a framework for how humans think; this theory provides principles of learning for the curriculum, instruction, and assessment embedded in Modeling Instruction. To situate this study within the historical context of science education and discuss Modeling Instruction, this chapter describes the following:

- Development of major pedagogical ideas in science education from the mid-1800s to the formation of Modeling Instruction;
- Constructivism and the Modeling Theory of Cognition;
- Curriculum, instruction, and assessment practices embedded in Modeling Instruction; and,

- Previous research results—including those with a focus on equity—that demonstrate the success of Modeling Instruction.

Each of these areas of discussion provide information related to this study, imparting guidance to the implementation of Modeling Instruction in AP Physics C: Mechanics and Electricity and Magnetism.

Historical Context

Prior to the mid-1800s, science and science education in the United States existed in an unstructured manner. However, the public's interest in science 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 (Spring, 2014). The final report from the Committee of Ten established a general framework for discussion of the goals of secondary education, including information about science education. All students—whether they intended to go to college or enter the workforce—were expected to participate in science courses and the scope of the science courses was expanded to include laboratory work. To specify which type of scientific experiments were expected from secondary students, Charles Eliot (President of Harvard and Chairman of the Committee of Ten) 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*. This list—along with information from other universities—became the first set of national standards for science (Bybee, 2010; Richardson, 1957).

Era of Scientific Management

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 a system with a focus on scientific management, success depended on the implementation of standardization. District and school administrators were preoccupied with standardizing all aspects of the school experience, including hiring procedures, evaluations of teachers and students, and curriculum, instruction, and assessment (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. Through the implementation of standardization, science—along with many other disciplines—became a set of facts to be memorized rather than experiences to be understood (Bybee, 2010). This sterilization eliminated the process of science, producing students who were 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" (p. 122). Further in the discussion, Dewey states, "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, p. 125). 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, p. 71). Even today—more than 100 years after Dewey's ideas—some textbooks begin with the scientific method; beginning with this formal structure as the only way to perform the scientific process presents an incorrect idea.

Establishing the National Science Foundation

Global events after World War II directly affected American schools (Spring, 2014); the Cold War between the United States and the Soviet Union caused many to question the existing K-12 school curriculum. “In the early 1950s the school curriculum, in particular, came under intense scrutiny and became an important ideological battleground on which partisan groups clashed as the nation’s survival seemed to hang in the balance” (Rudolph, 2002, p. 10). To increase the quantity and quality of science and technology workers in the United States, the federal government slowly began to provide funding to K-12 education. One application of funding for science was the National Science Foundation (NSF); established in 1950, its primary mission was to initiate, support, and promote basic scientific research and education (Mazuzan, 1994). Four divisions were created in the NSF: “Medical research; mathematical, physical, and engineering sciences; biological sciences; and scientific personnel and education" (Mazuzan, 1994, p. 6). Alan Waterman, chief scientist at the Office of Naval Research and previously a physics professor at Yale, became the first Director of the NSF; his appointment created a dependable link between the scientific elite and government funds from the NSF.

Waterman and other leaders quickly positioned the organization as the preeminent science—and science education—organization in the United States. Leaders of the NSF focused their efforts at improving K-12 science education by funding summer institutes for teachers and updating curricula. As the NSF engaged in K-12 education, science education professional organizations were excluded; this exclusion "demonstrates the overriding influence of both national security and the scientific elite in redefining the school curriculum in the 1950s" (Rudolph, 2002, p. 58). Leaders at the NSF were frustrated by approaches to science education taken by science educators and science education professional organizations; to direct curriculum and instruction developments funded by the NSF, the leaders wanted a first-rate scientist. A scientist would approach curriculum and instruction initiatives with the same techniques that were successfully used to conduct wartime research and development projects, leading to full implementation of the curriculum and instruction.

Legislators in Congress moderately increased federal funding to all divisions of the NSF during the early and mid-1950s, but sentiments of the legislators changed dramatically when the Soviet Union launched *Sputnik I* in 1957. In response, Congress passed the National Defense Education Act (NDEA) in 1958; Title III of the NDEA "appropriated $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 science, mathematics, and modern foreign languages" (Spring, 2014, p. 370). Funding for education could have been awarded to other agencies; instead, resources went to the Divisional Committee of Scientific Personnel and Education of the NSF. To lead the curricular reform efforts, leaders of the NSF could have partnered with professional science education organizations; however, leaders of the NSF wanted "someone very much like themselves, who shared the interests of the hard-science elite that dominated the NSF hierarchy" (Rudolph, 2002, p. 83). Jerrold Zacharias—physicist at MIT and member of the United States Office of Defense Mobilization's Science Advisory Committee—perfectly fit the description of an ideal candidate. With funding from the NSF, Zacharias created a group that began the process of improving curriculum and instruction in science education; whereas the group's ideas about education were radical at the time, the ideas have become integrated fully in all modern science education pedagogies.

Physical Science Study Committee

The Physical Science Study Committee (PSSC) was formed in the fall of 1956 by Zacharias, who quickly added other members of the scientific elite: Massachusetts Institute of Technology (MIT) president James Killian, Polaroid founder Edwin Land, Educational Testing Service president Henry Chauncey, and other prominent physicists from elite higher education institutions (Rudolph, 2006). Zacharias—and other members of the PSSC—had previous experience with large-scale scientific research and development projects; these projects were successful because scientists used a broad-based, analytical approach to solve complex problems (Rudolph, 2002). The PSSC approached curriculum development with the same methodology, integrating emerging technologies into goal-directed systems to create high-quality curriculum and instructional methods.

Up to and during the 1950s, most high school physics courses were delivered by textbooks. In the most popular science textbook, there were no descriptions of experiments or graphs showing the results of experiments that would justify any of the book's many assertive statements. In addition, the textbook did not have an accompanying laboratory program; for students in a course with this textbook, science was equated with vocabulary (Haber-Schaim, 2006). Zacharias had a different perspective about the teaching of physics; his ideas led to a unique course. Physics was not to be presented as a body of unchanging facts that students must memorize; rather, physics is best understood as living discipline with which students engage. Although one goal of the PSSC course was that students would learn physics content, the other goal of the PSSC course emphasized the process of reasoning from empirical evidence. “The question Zacharias hoped to get students to ask themselves at all times was ‘how do you know?’ What was your ‘basis for belief’ in any assertion about how the world works?” (Rudolph, 2002, p. 122). These questions formed the most important lesson for any student leaving a physics course designed by the PSSC: Students should understand that knowledge of the world is based on evidence.

To have students understand that evidence drives knowledge about physics (or any other subject), Zacharias envisioned the physics course using any set of materials that were useful for learning by the students; these materials included films, slides, textbooks, ancillary reading, and laboratory apparatus (Haber-Schaim, 2006). The laboratory activities—coupled with other materials—would “enable students to develop a deeper understanding of the dialectical march from experiment to theory and back again” (Rudolph, 2002, p. 130). While revolutionary at the time, the idea of placing the process of science on equal status as science content has been broadly accepted and implemented at all levels by the science education community. The *Next Generation Science Standards* (NGSS Lead States, 2013) and many state science standards—including South Carolina’s (South Carolina Department of Education, 2014)—contain statements that students from kindergarten to upper-level secondary courses should act like a scientist, using laboratory materials to determine evidence and construct arguments from the evidence. One of the lasting effects of the PSSC is the mainstream implementation of the scientific process into science courses; this legacy has been carried by other instructional approaches.

Another important aspect in the curricular and instructional methods of the PSSC are foundational principles. Science was to be presented as a human endeavor, allowing students to understand that anyone can do science (Haber-Schaim, 2006). The selection of topics was crucial for students to understand this idea; 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 for science education: Scientific and engineering practices; crosscutting concepts; and, disciplinary core ideas. These dimensions incorporate many of five essential ideas about science developed by the PSSC and place the science process and content on an equal status; information and organization of this framework echoes the ideas of Zacharias and work by the PSSC.

Influence of Robert Karplus

In the 1960s and 1970s, science education continued to evolve. Robert Karplus—a theoretical physicist and head of the Science Curriculum Improvement Study (SCIS) at the University of California, Berkeley—was one of the leaders during this era. Karplus and colleague Herb Thier utilized psychological research from the work of Jean Piaget and Jerome Bruner to create a practical program for students in grades K-6 (Kratochvil & Crawford, 1971). The curricular ideas for the program were constructed from a set of three guidelines:

1. The experiential and conceptual aspects of teaching should be distinguished from one another.
2. The curriculum construction should use major theories of intellectual development and learning, even if the theories provide conflicting interpretations.
3. The curriculum should have learning cycles with three phases: Exploration, invention, and discovery. (Karplus, 1969)

These guidelines provided students with experiences that differed from those they have outside of science courses; the experiences were unique, unusual, and engaging, affording students the opportunity for discovery (Bybee, 2010).

One of the lasting legacies by Karplus and others at the SCIS is the idea of a learning cycle (Karplus, 1969). The learning cycle provides a framework for the organization of curriculum, instruction, and assessment; this framework allows course designers to sequence activities to maximize student achievement. The SCIS learning cycle consisted of three phases: Exploration, invention, and discovery. During the exploration phase, the learner is allowed to impose their 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; from this conflict, 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 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 has become embedded in science education, having substantial research support and widespread application through textbooks on science teaching and learning.

Modeling Instruction

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; these workshops positively influenced his view towards teaching (Wells, Hestenes, & Swackhamer, 1995). Wells became a "hands-on" teacher, always eager to build his own apparatuses that provided simple demonstrations of deep physics. The high school in which Wells taught was near Arizona State University (ASU); Wells participated in many science and education courses at ASU throughout his high school teaching career. Eventually, Wells decided to complete his doctoral degree in physics education at ASU. Wells joined the Hestenes group for his research, so Hestenes became Wells' advisor. Wells wanted to perform research that would greatly contribute to the field of physics education; Wells and Hestenes discussed possibilities for several years. During the time of these discussions, Hestenes also was 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 et al., 1995). Wells administered the *Mechanics Diagnostic* test with his students, expecting the students to score highly on the assessment. However, 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 et al., 1995). The decision by Wells to improve his teaching practice launched his doctoral research, ultimately leading 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 et al., 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 et al., 1995). Wells created a version of Modeling Instruction that was laboratory-based and adapted to scientific inquiry. It emphasized the use of models to describe and explain physical phenomena rather than solve problems, aiming to teach modeling skills as the essential foundation for scientific inquiry. To accomplish this in a systematic fashion, Wells developed the Modeling Cycle (Wells et al., 1995). By the end of Wells' doctoral work, the modeling method could be described as cooperative inquiry with modeling structure and emphasis (Wells et al., 1995). After further refinement over several years, the Modeling Cycle was designed to have two stages: Model development and model deployment (Wells et al., 1995). As a rough comparison with Karplus' work, model development encompassed the exploration and invention stages of the learning cycle whereas model deployment corresponded to the discovery stage (Wells et al., 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 and instructional materials. Resources for Modeling Instruction (AMTA, 2017b) have been created for physics, chemistry, biology, physical science and middle school science, with future work directed towards elementary school science. Hestenes (1987, 2006, 2010, 2015, & 2016) has continued to develop the theoretical foundations of Modeling Instruction, utilizing information and methods from philosophy and cognitive psychology.

Table 2.1

Comparison of Pedagogical Ideas throughout the History of Science Education

Timeframe	Person / Organization	Pedagogical Ideas
Mid-1800s to 1900	Charles Eliot / Committee of Ten	Laboratories included in science courses; List of laboratories became the first set of national science standards
1900 to the end of World War II	School Boards throughout the United States	Era of scientific management whereby school boards sought to create standardized and efficient school systems
1950s to 1960s	Jerrold Zacharias / PSSC	Focus on scientific content and process of science; Big question for students to answer: "How do you know?"
1960s to 1970s	Robert Karplus / SCIS	Learning Cycle: Exploration, invention, discovery
1980s to current	Malcolm Wells, David Hestenes / AMTA	Modeling Theory of Cognition; Modeling Cycle: Model construction, model refinement, model application

Constructivism

Constructivism is an epistemological view of knowledge acquisition that emphasizes knowledge construction—the process of generating new knowledge structures from new information by synthesizing the new information with prior knowledge structures. Constructivism has matured since the mid-twentieth century, with several theories—most prominently by Jean Piaget and Lev Vygotsky—having distinct views about the nature of human learning. Despite the differences, most constructivists agree on four central characteristics that influence learning: “1) learners construct their own learning; 2) the dependence of new learning on students’ existing understanding; 3) the critical role of social interaction, and; 4) the necessity of authentic learning tasks for meaningful learning” (Applefield, Huber, & Moallem, 2001, p. 38).

A constructivist approach to education views students as meaning-makers; students use new information and prior knowledge structures to generate new knowledge structures. Teachers develop complex and authentic learning experiences for students, which provides an opportunity for students to actively engage in problem-solving and critical thinking (Kanselaar, 2002). Teachers consider prior conceptions that students bring to school because new knowledge structures are highly dependent on prior knowledge structures (Jones & Brader-Araje, 2002). In addition to these, Jonassen (1994) proposed 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.

These characteristics provide a way for students to create knowledge structures in a variety of domains, allowing students to more easily transfer skills and knowledge. Though differences exist between theories in constructivism, the Modeling Theory of Cognition and Modeling Instruction are unconcerned with the differences. The Modeling Theory of Cognition and Modeling Instruction focus more attention on the general ideas of constructivism, combining these ideas with other pedagogical techniques.

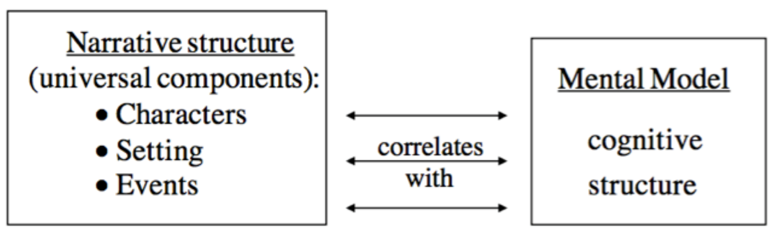

Figure 2.1. Prototypical example of cognition as the construction of a narrative; the narrative generates construction of a mental model. From "Modeling Theory and Modeling Instruction for STEM Education" by D. Hestenes, 2015, *epiSTEME 6 International Conference to Review Research on Science, Technology and Mathematics Education*. Copyright 2015 by David Hestenes. Reprinted with permission.

Modeling Theory of Cognition

The Modeling Theory of Cognition builds on constructivism by positing that humans construct mental models to understand the world. Figure 2.1 provides a prototypical example of cognition, which is the comprehension of a narrative. The narrative may be read or heard using language (for example, telling a story) or observed using the senses (for example, a hunter using hoof prints to track a deer); both methods generate a mental model. The use of language between two people activates a mental model for both the producer and receiver, facilitating a coordination of mental models

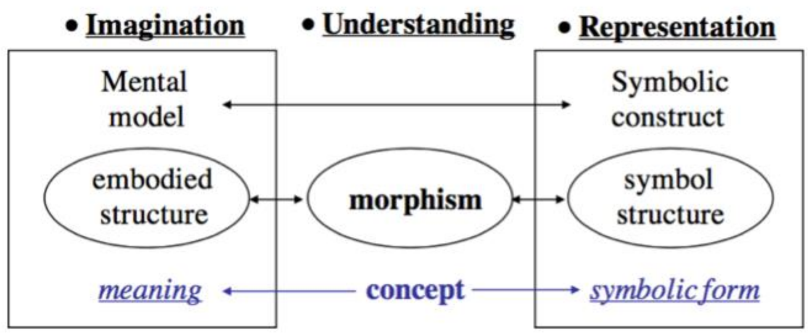

Figure 2.2. Modeling theory of cognition relating imagination, understanding, and representation. From "Modeling Theory and Modeling Instruction for STEM Education" by D. Hestenes, 2015, *epiSTEME 6 International Conference to Review Research on Science, Technology and Mathematics Education*. Copyright 2015 by David Hestenes. Reprinted with permission.

between the producer and receiver. In this framing of cognitive linguistics, known as cognitive semantics, "language does not refer directly to the world, but rather to mental models and components thereof! Words serve to activate, elaborate or modify mental models" (Hestenes, 2006, p. 11).

As a person constructs a mental model, they generate a concept using the process in Figure 2.2. The person creates a mental model and provides an embodied structure, which establishes meaning for the mental model. A morphism—defined as an analogy that preserves form—allows the person to develop a symbol structure. In conjunction with the symbolic construct and symbolic form, the mental model is elevated to a concept. This is defined as a (form, meaning) pair, allowing the person to communicate their concept with others.

Figure 2.3 provides further information on the definition of a concept. The symbolic form of a concept is defined by three parts: A symbol is the public method of illustrating a concept, the form is the framework of the concept, and the meaning is an individual's interpretation of the concept. For example, consider the concept of

Figure 2.3. Schema of a concept and conceptual model. "Modeling Theory and Modeling Instruction for STEM Education" by D. Hestenes, 2015, *epiSTEME 6 International Conference to Review Research on Science, Technology and Mathematics Education*. Copyright 2015 by David Hestenes. Reprinted with permission.

"position." The symbols (x, y, z) are one option for public representation, the form is developed from the geometric structure of space and defined by a coordinate system, and the meaning is that an object is located at the place in space defined by the coordinate system and numbers for each of x, y, and z.

Figure 2.3 also provides a definition for a conceptual model, which follows the same form as a concept. Representations are the public method for describing the concepts in a conceptual model, the structure is the framework of the concepts in a conceptual model, and the referent is an individual's mental model of the concepts in a conceptual model (Hestenes, 2015). Because conceptual models are public, the representations and structure are determined by group consensus; however, these may change if the group determines that another representation or structure better symbolizes the conceptual model.

Figure 2.4 describes the interaction between personal mental models, conceptual models, and the physical world. The crucial distinction is between the mental world and conceptual world; the mental world contains an individual's models, whereas the conceptual world includes the scientifically accepted conceptual models. The goal of science education is to help students transform their mental models into agreement with the conceptual models, leading to a sophisticated understanding of the physical world.

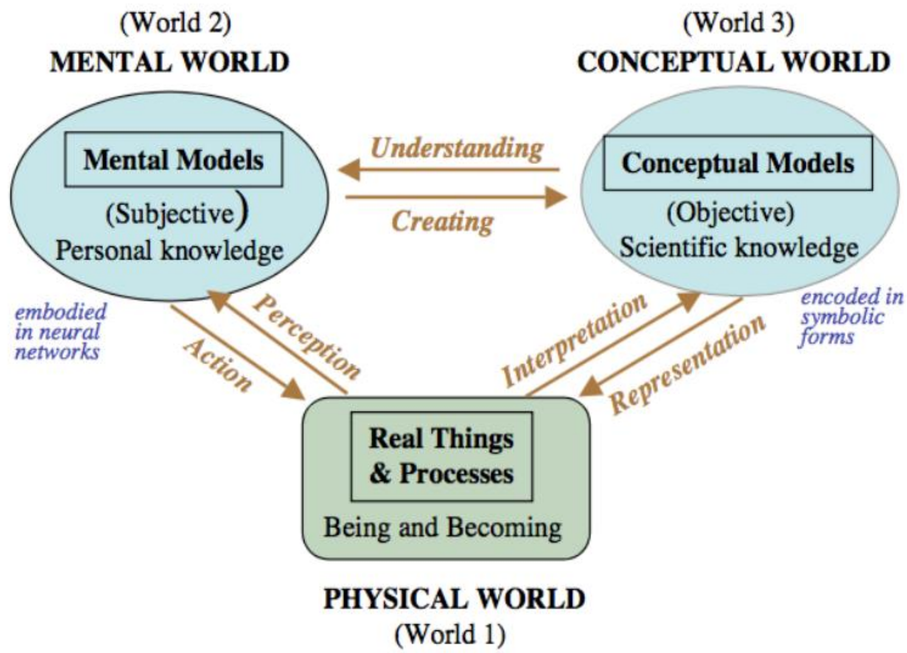

Figure 2.4. Relationships between the physical, mental, and conceptual worlds (Hestenes, 2006, p. 10). From "Notes for a Modeling Theory of Science, Cognition and Instruction" by D. Hestenes, 2006, *Proceedings of the 2006 GIREP Conference*. Copyright 2006 by David Hestenes. Reprinted with permission.

This goal is accomplished by determining student preconceptions, providing an opportunity to change their conceptions through laboratory activities or thought experiments, and reinforcing the new conceptions through further laboratory activities or other methods.

The Modeling Theory of Cognition explains how humans use information to build a model, both personally with mental models and collectively with conceptual models. In addition to the process of building a model, the Modeling Theory of Cognition uses a specific definition for the term model: "A model is a representation of structure in a system of objects" (Hestenes, 2015, slide 15). A system is a set of related objects, which may be real or imaginary, physical or mental, or simple or composite; the system itself is known as the referent of the model (Hestenes, 2016). The structure is the set of relations

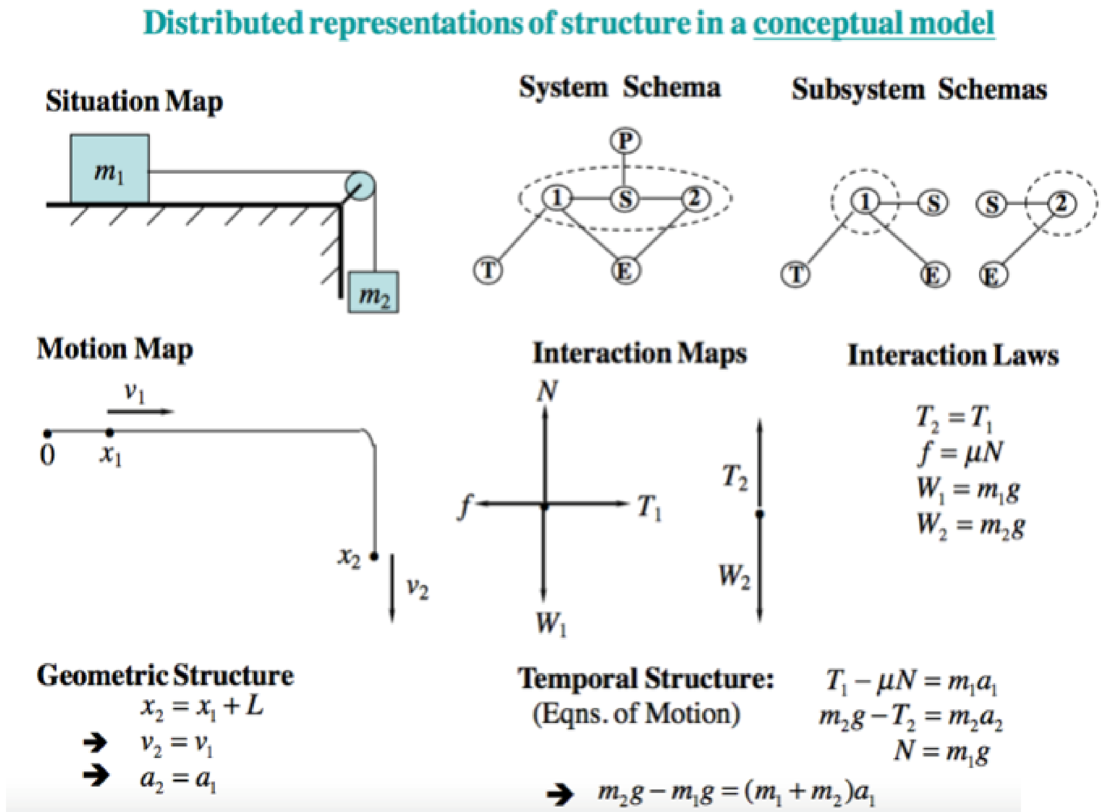

Figure 2.5. Example of structure in the unbalanced force model. From "Modeling Theory and Modeling Instruction for STEM Education" by D. Hestenes, 2015, *epiSTEME 6 International Conference to Review Research on Science, Technology and Mathematics Education*. Copyright 2015 by David Hestenes. Reprinted with permission.

among its objects, with four types of structure are sufficient for a model in any scientific discipline:

a) Systemic structure specifies composition, object properties, and causal links;

b) Geometric structure specifies configuration and location in a reference frame;

c) Interaction structure specifies interaction laws for causal links; and,

d) Temporal structure specifies changes in state variables (Hestenes, 2015).

In general, representations include verbal and written communication, mathematics, diagrams, graphs, and computational programming; however, each type of structure has specific representations. Figure 2.5 provides a full set of representations of the structure of the unbalanced force model, which is an important model in physics that is best known for Newton's second law ($\sum \vec{F} = m\vec{a}$).

Modeling Instruction

Although many authors (Gilbert, 2011; Lattery, 2017; Windschitl, Thompson, & Braaten, 2007) discuss model-building in science education, Modeling Instruction is a unique version of models-based science education. Modeling Instruction incorporates the ideas of the Modeling Theory of Cognition to integrate curriculum and pedagogy: "The curriculum is organized around a small number of conceptual models as the content core of each scientific domain; the pedagogy promotes scientific literacy centered on making and using models as the procedural core of scientific knowledge" (Hestenes, 2015, slide 27). This integrated approach creates a focus on models and modeling, leading to the overarching instructional objectives of Modeling Instruction:

a) A clear concept of a model, including qualitative and quantitative aspects;
b) Familiarity with a basic set of models as the core of the science content;
c) Skills in the techniques of modeling, especially the relationship between diagrammatic and symbolic representations; and,
d) Experience in the deployment of models to understand the physical world (Hestenes, 2015).

The integrated approach also confronts impediments to learning science: Misconceptions about science content; a view of science as a fragmented set of facts, rules, and formulas; and, misconceptions about the scientific method and scientific inquiry; (Hestenes, 2015). When students build conceptual models for scientific concepts, science becomes a living discipline; students can see connections between the facts, rules, and formulas and understand how science content fits together in a model. Students act as scientists when using the modeling process to create models, developing and refining their laboratory skills. By integrating curriculum and pedagogy, Modeling Instruction addresses impediments for learning science and provides a purpose for inquiry-based laboratory activities; the result is a coherent science course focused on models and modeling.

Modeling Cycle

The Modeling Cycle has three phases: Develop an initial model from data and analysis in an introductory laboratory activity (known as a paradigm lab); create a fully-constructed model by refining and expanding the model through discussion and further laboratory activities; and, apply the fully-constructed model through written practice, engineering design challenges, or laboratory activities (Megowan-Romanowicz, 2016). To begin the paradigm lab, the teacher provides a demonstration of a testable phenomenon—for the constant velocity model (the first model in the physics sequence), this is a buggy rolling along a table or floor. Students discuss observations of the demonstration, agree on two variables to quantify and correlate, and predict expected outcomes of the relationship between the variables. Students collaborate in small groups to plan and conduct data collection, analyze data, and share findings with the rest of the class via whiteboards. Students critically examine their scientific and engineering practices throughout this process (NGSS Lead States, 2013), refining their data collection and analysis techniques. Information from the paradigm lab is represented through diagrams, graphs, and equations; these representations form the foundation of a constant velocity model. The constant velocity model is then refined and expanded through further laboratory activities, with students justifying any updates or additions based on evidence.

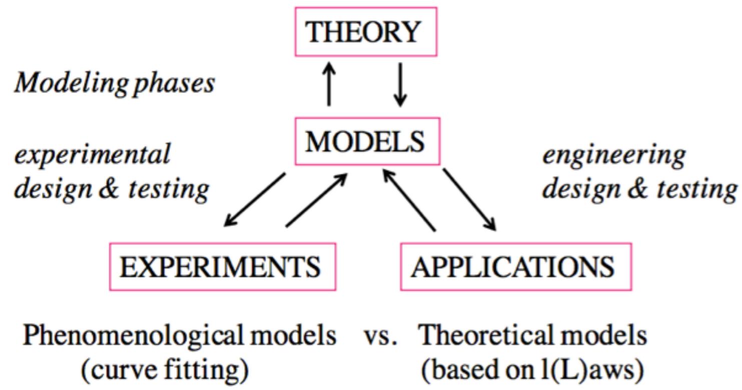

Figure 2.6. Overview of Modeling Instruction; scientific models are the content core and modeling is the procedural core of each science. From "Modeling Theory and Modeling Instruction for STEM Education" by D. Hestenes, 2015, *epiSTEME 6 International Conference to Review Research on Science, Technology and Mathematics Education*. Copyright 2015 by David Hestenes. Reprinted with permission.

The constant velocity model is applied to novel situations in a variety of contexts, which test the limits and explanatory power of the model. After completing the Modeling Cycle, each student has an in-depth constant velocity model containing diagrams, graphs, and equations. Students understand the development of the constant velocity model from the paradigm lab to applications, including limitations of the model. Students then begin the Modeling Cycle again with the next model, repeating the process until the course is finished. Figure 2.6 illustrates the relationship between theory, models, experiments, and applications in the Modeling Cycle.

Classroom Discourse and Whiteboards

Classroom discourse is another major aspect of Modeling Instruction. Students use whiteboards—24" x 36" erasable pieces—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 classroom discourse about the results. As students apply the model in novel situations through problem-solving, they use the whiteboards to show their work; the whiteboards become filled with multiple representations, including mathematics, diagrams, and graphs. Students argue for their solution by clearly articulating their solution; having the representations on a large whiteboard allows the students to argue for their solution more convincingly. If the students have misconceptions in their solution, the instructor (or other students) are allowed to question the work and help the students correct their misconceptions. Developing a vibrant classroom discourse is a crucial skill for teachers who use Modeling Instruction (Desbien, 2002; Megowan, 2007) because this process helps students deeply understand the modeling process and models.

Modeling Instruction aligns with scientific practice because scientific practice is model-centered. Models are basic units of coherently-structured knowledge from which humans can make logical inferences—predictions, explanations, plans, and designs. Models form the basis of all theories because models can be directly compared to the physical world; "a theoretical hypothesis or general principle cannot be tested empirically except through incorporation in a model" (Hestenes, 2015, slide 25). Models are embodied in the minds of individuals through their physical intuition; this allows scientists to share and compare models as they develop or expand theories. For information on models in AP Physics C: Mechanics and Electricity and Magnetism, see Appendices A, B, C, and D.

Modeling Instruction and Current Views of Learning

Modeling Instruction aligns with current views of learning. The American Psychological Association's Coalition for Psychology in Schools and Education (APACPSE) lists the top 20 principles from psychology for teaching and learning in pre-kindergarten through twelfth grade (APACPSE, 2015); the first 8 principles discuss student thinking and learning. Principle 2 states, "What students already know affects their learning" (APACPSE, 2015, p. 1). Modeling Instruction addresses this by beginning the Modeling Cycle with a paradigm laboratory. This lab allows students to incorporate prior knowledge, developing their model with the prior knowledge and information from the lab. APACPSE (2015) asserts that "learning is based on context, so generalizing learning to new contexts is not spontaneous but instead needs to be facilitated" (p. 1) in Principle 4. During the second and third stages of the Modeling Cycle, students use the model in new contexts; this allows students to transfer knowledge from the initial application of the model new applications, generalizing their learning. Another idea is Principle 5: "Acquiring long-term knowledge and skill is largely dependent on practice" (APACPSE, 2015, p. 1). Modeling Instruction embeds practice throughout the Modeling Cycle because students are consistently returning to the model through further laboratory activities and application problems. Student spend a significant amount of time on each model, developing a robust set of representations for the model. Principle 6 states, "Clear, explanatory, and timely feedback to students is important for learning" (APACPSE, 2015, p. 1). Throughout the Modeling Cycle, students participate in whiteboarding sessions; during this time, the teacher or other students provide feedback on the information on the whiteboard. This creates a classroom community focused on learning, allowing students to refine their model. APACPSE (2015) asserts that "student creativity can be fostered" (p. 1) in Principle 8; during the Modeling Cycle, students are encouraged to be creative (within the rules of safety) with their laboratory procedures and problem-solving. Students are expected to apply their model in novel applications, showing a full development of their model.

Brown, Roediger III, and McDaniel (2014) provide a different view of learning in the book *Make It Stick*. The authors claim that "learning is deeper and more durable when it's *effortful*" (Brown, Roediger III, & McDaniel, 2014, p. 3). Modeling Instruction forces students to engage while creating a model; students begin a paradigm laboratory with a lack of understanding of the model. As students work through the Modeling Cycle and generate a mental model with multiple representations, they achieve a deep understanding of the model. Another idea from Brown et al. (2014) is that "when you're adept at extracting the *underlying principles* or '*rules*' that differentiate types of problems, you're more successful at picking the right solution in unfamiliar situations" (p. 4). Generating underlying principles is intrinsic in Modeling Instruction because models are basic units of knowledge; as students refine the model, they apply the model in novel situations. This process helps students to understand the parts and limits of the model, allowing students to choose the correct model when faced with an ill-defined problem. Brown et al. (2014) also discuss that "all new learning requires a *foundation of prior knowledge*" (p. 5). Models build on each other, so students have a foundation on which to base future models; when a model fails to account for empirical data, students must create a new model. As students move through a science course, they see relationships and understand the connection between models. A further idea from Brown et al. (2014) is that "people who learn to *extract the key ideas from new material and organize them into a mental model* and connect that model to prior knowledge show an advantage in learning complex mastery" (p. 6). Modeling Instruction teaches students how to generate a model using multiple representations, helping students to achieve highly in science courses.

Modeling Instruction is an important step in the pedagogy of science education, connecting the Modeling Theory of Cognition and other modern views of learning with curricular and instructional choices to maximize learning. The Modeling Instruction classroom is focused on models and modeling, with the expectation that each student works to align their mental model with the accepted scientific model. Students interact throughout all parts of the Modeling Cycle, comparing results and challenging each other during problem-solving sessions. This student interaction produces a high level of discourse in the classroom, helping students to communicate, collaborate, and critically think about their models.

Previous Research Results

Modeling Instruction research has been conducted by many in the Physics Education Research (PER) community, beginning with work by Hestenes, Halloun, Wells, and others in the mid-1980s. Modeling Instruction began in high school physics courses, so these courses have the highest number of research articles; however, Modeling Instruction has expanded to university-level physics courses and other high school and middle school science courses. Because AP Physics C: Mechanics and Electricity and Magnetism sits at the intersection of high school and university-level physics, the previous research results will focus on both areas.

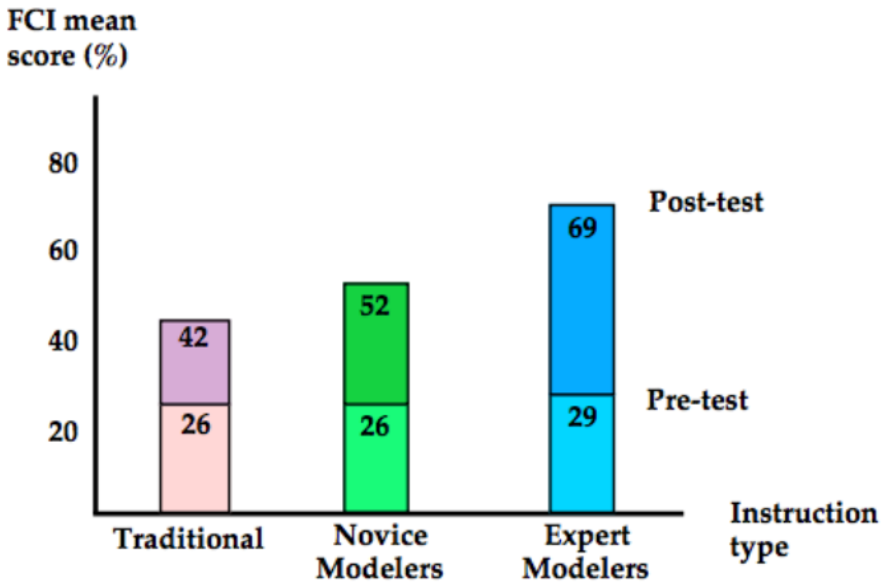

Figure 2.7. FCI mean pretest and posttest scores under different instruction types. From "Notes for a Modeling Theory of Science, Cognition and Instruction" by D. Hestenes, 2006, *Proceedings of the 2006 GIREP Conference*. Copyright 2006 by David Hestenes. Reprinted with permission.

High School Physics 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. Modeling Instruction—and other pedagogical techniques—use the Force Concept Inventory (FCI) to determine the growth of students in introductory physics courses; due to widespread adoption in the PER community, the FCI "has become the most widely used and influential instrument for assessing the effectiveness of introductory physics instruction" (Jackson, Dukerich, & Hestenes, 2008). Figure 2.7 shows aggregated data from a nationwide sample of 7500 high school physics students involved in the *Modeling Instruction Project* during 1995-1998 (Hestenes, 2006). The average pretest FCI mean score is slightly above a random guessing mean of 20% for all three instructional types (see from the lower number in the bar graph); the upper number in the bar graph shows the posttest FCI mean score. The traditional instruction type—characterized by lectures, demonstrations, and standard laboratory activities—shows the smallest posttest FCI mean score, whereas gains from students in Modeling Instruction classrooms are higher. The Modeling Instruction data is broken into two parts: Novice Modelers and Expert Modelers. Novice Modelers were teachers who are in their first year implementing Modeling Instruction, after completing an intensive three-week workshop. Expert Modelers were teachers who completed multiple three-week workshops and implemented Modeling Instruction for more than two years (Hestenes, 2006). Students in the classrooms of Novice Modelers achieved a posttest FCI mean score of 51%; students in the classrooms of Expert Modelers attained a posttest FCI mean score of 69%. Teachers from other workshops after 1998 have also given the FCI to their students, with students from these teachers' classrooms consistently achieving posttest FCI means scores in the 80-90% range (Hestenes, 2006).

Wells performed the seminal study of Modeling Instruction, comparing three courses: An inquiry-based physics course taught by Wells; a models-based physics course taught by Wells; and, a traditional physics course taught by a colleague of Wells' (Wells et al., 1995). In the inquiry-based course, students performed laboratory activities during 70% of class time and spent the remaining 30% of class time on in-class problem-solving. For the modeling course, students performed laboratory activities and solved problems at the same class-time breakdown as the inquiry course; however, Wells systematically emphasized models and modeling, which increased the coherence of the physics course. In the traditional course, the teacher lectured and demonstrated physics principles for 80% of the class time, with the remaining 20% focused on laboratory activities. All three courses had approximately the same number of students and covered the same topics in mechanics at the same time. 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 2.2 "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 et al., 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 et al., 1995).

Table 2.2

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.

Wright (2012) compared two classes at a high school in rural Tennessee: One taught with Modeling Instruction (treatment group), the other taught with traditional lecture instruction (control group). Wright used a randomized control group pretest-posttest design; students were randomly grouped, given the FCI as a pretest, received instruction according to their group, and given the FCI again as a posttest. Students in the Modeling Instruction group scored higher on the FCI to a statistically significant level, showing that Modeling Instruction was effective at increasing the academic achievement of students in high school physics (Wright, 2012).

Arseneault (2014) conducted a study on the effect of Modeling Instruction in a Louisiana high school physics classroom. Arseneault taught two classes with traditional instruction and two classes with Modeling Instruction; each instructional group contained one regular physics class and one honors class. The four classes received equal amounts of time on topics, with Arseneault utilizing 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 2.7 from Novice Modelers.

University-Level Physics Results

Brewe (2002) used students in freshmen calculus-based physics classes at two different universities to determine the effect of Modeling Instruction. Students at Arizona State University (ASU) were taught using Modeling Instruction; students at North Carolina State University (NCSU) were taught with traditional lecture instruction. Students were given common exam problems and the FCI; 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 ASU students group had a higher posttest score, and showed higher gains; at a minimum, the ASU students received a reasonable treatment of force concepts (Brewe, 2002). For the common exam problem analysis, the ASU students outscored the NCSU students. Class means for Problems #1 and #2 were significantly different at the .01 level (Brewe, 2002), which indicates Modeling Instruction had a positive impact on the problem-solving ability of students.

Desbien (2002) compared honors and regular courses at North Carolina State University (NCSU), Chandler-Gilbert Community College (CGCC), and Arizona State University (ASU) in the late 1990s and early 2000s, using nine sections from the college/universities. One NSCU section was taught with an interactive/Socratic instructional style, two CGCC sections were taught with Modeling Instruction, and two of the six ASU sections were taught with Modeling Instruction. Students in the nine sections were given the FCI as a pretest at the beginning and posttest at the end of the course; raw gains were calculated for each section by subtracting the average of student scores on the pretest from the average of student scores on the posttest. Student gains varied among the institution and instructional style: Students at NCSU had a raw gain of 30%; students in the non-Modeling Instruction courses at ASU had raw gains of 15%, 15%, 17%, and 19%; students in the Modeling Instruction courses at ASU had raw gains of 26% and 30%; and, students in the two sections at CGCC—taught with Modeling Instruction—had the highest raw gain, with one section increasing 51% and the other section increasing 41%. With this information, Desbien concluded that Modeling Instruction is a more effective technique for teaching forces than other instructional techniques.

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, both Wells and the traditional teacher had students in both non-honors and honors courses (Wells et al., 1995). 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 a largely minority public school in urban Phoenix, Arizona (Melendez & Wirth, 2001). Students were successful on their evaluations; Melendez and Wirth attribute the success to Modeling Instruction, an integrated approach, and extended time in class. 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 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. (2010) implemented Modeling Instruction in introductory calculus-based physics at Florida International University; changing this course was a part of efforts to increase the number of historically under-represented students in physics and science. 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; 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, p. 7). 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

Science education in the United States has transformed from the de facto national standards established by the Committee of Ten, through the heady days of the PSSC, and into the next advancement of Modeling Instruction. With a foundation in constructivism and the Modeling Theory of Cognition, Modeling Instruction connects curriculum and pedagogy to focus on models as the content core of science courses and modeling as the process for performing science. Modeling Instruction addresses alternate student conceptions and aligns with modern views of learning, helping students to see science as an interconnected set of ideas. Modeling Instruction has a robust research base, with many studies at the high school and university levels discussing the positive impact of Modeling Instruction. Studies also show that Modeling Instruction is a favorable method of instruction for students who have been typically underrepresented in science and engineering; using Modeling Instruction is a promising way to boost underserved students.

CHAPTER THREE: Action Research Methodology

Modeling Instruction is a pedagogy that places models at the center of science learning. Constructivist learning principles and the Modeling Theory of Cognition form the philosophical foundation of Modeling Instruction and students use the Modeling Cycle to develop conceptual 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. However, 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 was to determine the viability of Modeling Instruction as a pedagogy for students in AP Physics C: Mechanics and Electricity and Magnetism. The proposed solution to the problem of practice was to incorporate Modeling Instruction theory and practice in my courses during the 2016-2017 school year. Because the viability of Modeling Instruction in AP Physics C: Mechanics and Electricity and Magnetism is unknown, the research question for this study is the following: Is Modeling Instruction a viable pedagogy in AP Physics C: Mechanics and Electricity and Magnetism?

Action Research Design

This study utilizes a quantitative action research design because I was interested in understanding the magnitude of the impact Modeling Instruction has on student achievement in AP Physics C: Mechanics and Electricity and Magnetism. Action research is performed by teachers, counselors, or administrators to improve their education practices. The basic process of action research consists of four steps: Identifying an area of focus; collecting data; analyzing and interpreting data; and, developing a plan of action (Mertler, 2014). Once the plan of action has been implemented, the researcher revises the original plan to make improvements—creating a new plan of action, which begins a new action research cycle.

Information on the Research Site

The site for this study was a large, suburban high school in the southeastern part of the United States. In 2016-2017, the high school had a student body of over 4,100 students, with an ethnic composition of 81% Caucasian, 13% African-American, 3% Hispanic, and 3% other. Approximately 43% were served by gifted and talented program, 8% were classified as students with disabilities, and 20% were considered "in poverty." The school provided 28 AP courses; these courses served approximately 41% of the student population, with 81% of students taking an AP course scoring a 3 or higher on the AP exam. The high school received an absolute rating of "Excellent" from the state Department of Education from 2010 to 2014 (the rating system is discontinued until 2018). The high school offered over 250 courses in a broad range of subjects: 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 academically: Members of the class of 2017 were awarded over 29.6 million dollars in scholarships, 400 students received recognition from their performance on Advanced Placement (AP) tests, nine seniors were named as a National Merit Finalist, and two seniors received appointments to a military academy. The school has been successful athletically, receiving the state Athletic Administrators Association Director's Cup for the largest classification for four consecutive years (2013-2014 through 2016-2017); this award is given to the school with the best combined performance of all sports. The school has been successful in the performing arts and other clubs: The school's Marching Band finished second at the Bands of America Super Regional and finished eighth in the Grand Nationals competition; the Dance program competed at the Contest of Champions and received an overall rating of Excellent; and, Student Council was named a 2017 National Gold Council of excellence. 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 a higher number of students than anticipated at the research site. The United States Census Bureau provided an estimate for the 2015 ethnic demographics of the community: 91.7% "White," 4.6% "Black or African American," 0.1% "American Indian and Alaskan Native," 2.0% "Asian," and 0.1% "Some other race." There is a generally positive relationship between the research site and community.

Study Participants

The participants of this study are students in my AP Physics C: Mechanics and Electricity and Magnetism courses during the 2016-2017 school year. To protect the identity of the participants and setting, pseudonyms are used throughout the study.

Table 3.1

Student Demographics in AP Physics C: Mechanics and Electricity and Magnetism

Course	Mechanics	Electricity and Magnetism
Total Number of Students	20	16
Number of Males	19	16
Number of Females	1	0
Number of Caucasian Students	19	15
Number of Hispanic Students	1	1

Prior to the study, I received permission from the school district's Office of Assessment and Evaluation, the school's principal, a parent/guardian of each student, and individual students (see Appendices E and F for further information regarding permissions). In addition to local permissions, I applied and received authorization for research from the Institutional Review Board (IRB) of the Office of Research Compliance of the University of South Carolina.

All participants in the study are twelfth-grade students, with demographics listed in Table 3.1. Though I attempted to recruit female and/or students from ethnic minorities at the research site, I have been unsuccessful recruiting these students. One issue has been that many students do not reach calculus; to enroll in AP Physics C: Mechanics and Electricity and Magnetism, the high school requires a pre- or co-requisite of a calculus course. Another issue has been the high number of other elective courses, especially in science. AP Physics C: Mechanics and Electricity and Magnetism competes with these courses for students; the other courses have been more successful in recruiting students. A future goal is to recruit more students of all characteristics into these courses.

Table 3.2

Student Prior Physics and Current Mathematics Courses

Course	Mechanics	Electricity and Magnetism
Total Number of Students	20	16
Number with Prior AP Physics 1 and/or 2	3	3
Number with Prior Honors Physics	10	7
Number with No Prior Physics	7	6
Number Currently Enrolled in Multivariable Calculus	2	2
Number Currently Enrolled in AP Calculus BC	13	10
Number Currently Enrolled in AP Calculus AB	2	1
Number Currently Enrolled in Honors Calculus	1	1
Number Currently Enrolled in No Mathematics Course	2	2

To compare the background of students in this study with students in previous studies, I collected data on any physics course taken prior to 2016-2017 and the mathematics course in 2016-2017. The College Board (2014) strongly recommends AP Physics C as a second-year course, though “the imaginative teacher can design approaches that best fit the needs of his or her students” (p. 7). If AP Physics C is a first-year course for students, the College Board recommends 90 minutes per day (450 minutes per week); the high school in the study is on a modified block schedule, with students in class approximately 95 minutes per day (475 minutes per week). With these requirements, students could opt to take AP Physics C as a first-year course; however, these students were required to receive a qualifying score on a pre-assessment before gaining enrollment (see Table 3.2 for information on the number of students with a physics course before 2016-2017).

Because AP Physics C is calculus-based, students were required to have a pre- or co-requisite of any calculus course. The high school offers three options: Honors Calculus, AP Calculus AB, and AP Calculus BC; most students in AP Physics C were enrolled or had finished one or two of these courses. Two students had completed AP Calculus BC prior to 2016-2017, so they enrolled and completed Multivariable Calculus through a local community college (see Table 3.2 for mathematics enrollment in 2016-2017).

Positionality and Ethical Considerations

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. I have been someone who enjoys thinking and explaining all my life, though I did not think about teaching as a career until my last year as an undergraduate. Although I excelled in physics research, I loved discussing physics topics with my classmates. This lead to graduate school in education to learn how to effectively teach physics; after graduating, I taught high school physics for two years. I left teaching to work at an engineering firm, preparing to become an electrical engineer. However, something was missing in my life; I realized that I should be teaching students about the beauty of physics, so I returned to the classroom. Feeling like I needed a way to grow as a teacher, I enrolled in the doctoral program. Through the coursework and research, this program helped me become a better teacher and provided a framework for future growth.

Due to the highly personal nature of action research, bias could be induced during the creation of the research plan, implementation, and analysis. I maintained a high level of ethics by using best practices to administer assessments and collect data. Although researchers have a temptation to maximize results through manipulation of data, I did not manipulate any data during the analysis. In addition, I fairly represented the results when discussing the conclusions; though student performance was lower than I hoped, this information helped me understand how to change the courses to improve outcomes for future students.

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 was privacy because data about the participants was collected for analysis. Personal identification was never associated with a particular student when collecting the data; student data was reported in the aggregate to further ensure students cannot be individually identified. The district in which the study was conducted explicitly provided an opportunity for students to opt out of any research without penalty, protecting students from possible physical, psychological, legal or other risks.

Another area of concern was the curricular organization and instruction students received. This dissertation used a teaching method that is different from other science pedagogies at the research site, so there could have been an issue for students who do not want to participate in the study. In addition, I was considered a Novice Modeler. Although this was my second year teaching AP Physics C, I had only hosted and participated in two one-week workshops; these workshops helped me learn the basics of Modeling Instruction, but the one-week workshops are less intense than the full three-week workshops. However, in all documents found for the literature review, there were no cases where students receiving Modeling Instruction performed more poorly than the student receiving traditional or inquiry-based instruction—even for Novice Modelers. 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.

Research Methods

To collect data for the research question, the study utilized both a one-group pretest-posttest design and one-shot case study. A one-group pretest-posttest design is a pre-experimental design that allows a researcher to gauge whether a change has occurred; students are observed or measured before and after a treatment condition is applied (Mertler, 2014). A one-shot case study is another pre-experimental design, in which the researcher applies a treatment condition and then measures an outcome (Mertler, 2014). The treatment condition was Modeling Instruction for both research designs, but each design used different assessments as measures of learning.

For the one-group pretest-posttest method, student information was collected on the following assessments:

- 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); and,

- Electricity and Magnetism Conceptual Assessment (EMCA).

In the one-shot case study, student scores from the 2017 AP Physics C: Mechanics and Electricity and Magnetism exams were collected. Simple statistical analysis—mean, median, standard deviation, range—were performed on the AP exams, FCI, MBT, BEMA, and EMCA, with accompanying graphs showing scores within or between assessments. Student scores on the assessments from the one-group pretest-posttest design and one-shot case study are used to discuss the viability of Modeling Instruction as a pedagogy for students in AP Physics C: Mechanics and Electricity and Magnetism.

The FCI, MBT, BEMA, and EMCA are all examples of concept inventories; these are "research-based assessment instruments that probe students' understanding of particular physics concepts" (Madsen, McKagan, & Sayre, 2016). Concept inventories allow researchers—in traditional or action research—to determine the effectiveness of particular curricular or instructional techniques. Each question in a concept inventory has been rigorously designed and tested, allowing researchers to draw conclusions about the effectiveness of the technique. Concept inventories vary in terms of research validation; Madsen, McKagan, and Sayre (2016) have created seven research validation categories:

1) Questions based on research into student thinking;
2) Studied with student interviews;
3) Studied with expert review;
4) Appropriate use of statistical analysis;
5) Administered at multiple institutions;
6) Research published by someone other than developers; and,
7) At least one peer-reviewed publication (p. 4).

If an assessment meets all seven criteria, it receives a “Gold” rating; between five and six criteria, a “Silver” rating; between three to four, a “Bronze” rating; and, between one and two a “Research-based” rating. These ratings allow researchers to choose appropriate concept inventories and understand any limitations about the concept inventory.

The FCI—rated as “Gold” by Madsen, McKagan, and Sayre (2017)—was created by David Hestenes, Malcolm Wells, and Gregg Swackhamer; this inventory was designed to probe student beliefs on force (Hestenes, Wells, & Swackhamer, 1992). The FCI requires students to choose between Newtonian concepts and commonsense alternatives, with results from the inventory showing good discrimination between Newtonian and commonsense thinking (Hestenes et al., 1992). The FCI contains 30 questions, which are arranged into 6 categories of Newtonian Concepts: Kinematics, first law, second law, third law, superposition principle, and kinds or force. These six conceptual dimensions are required for the complete force concept; the FCI probes student understanding in each dimension by questions of more than one type (Hestenes et al., 1992).

The FCI is one of the most-researched instruments in Physics Education Research (PER), with many studies using the FCI to assess a new pedagogical approach to physics instruction (Arseneault, 2014; Beichner, 2009; Desbien, 2002; Hake, 1998; Hestenes, 2016; Jackson, Dukerich, & Hestenes, 2008; Melendez & Wirth, 2001; O’Brien & Thompson, 2009; Von Korff et al., 2016; Wright, 2012). Researchers have produced papers discussing the interpretation of FCI scores (Coletta & Phillips, 2005), proposed separating the FCI into two equivalent half-tests (Han et al., 2015), and using factor analysis to understand how student understanding evolves (Semak, Dietz, Pearson, &

Willis, 2017). Other researchers have criticized the FCI (Henderson, 2002), though these concerns have been defended by the PER community. After 25 years of research, the FCI remains a foundational assessment tool for mechanics research; used with the MBT, researchers receive a relatively complete profile of a student's understanding of mechanics.

To accompany the FCI, David Hestenes and Malcolm Wells created the MBT—rated as "Bronze" by Madsen et al. (2017). Questions on the FCI were designed to be meaningful to students without any training in mechanics, eliciting their preconceptions about the subject. In contrast, students should proceed through a mechanics course before understanding the concepts on the MBT (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; and gravitational free-fall and friction in specific forces. Though the Baseline may appear to be a conventional problem-solving test, the main intent is to assess qualitative understanding. Distractors include typical student mistakes rather than commonsense alternatives, with problems requiring students to do more than simply input numbers into an equation (Hestenes & Wells, 1992). Because the FCI and MBT are complementary probes to determine student understanding of basic mechanics concepts, taking the information from the FCI and MBT together provides a fairly complete profile of student understanding (Hestenes & Wells, 1992).

The BEMA—rated as "Gold" by Madsen et al. (2017)—was developed in 1997 by Ruth Chabay, Bruce Sherwood, and Fred Reif to measure 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 a calculus-based electricity and magnetism (E&M) physics curriculum (Ding et al., 2006). BEMA was designed to incorporate broad coverage of E&M topics instead of probing particular E&M concepts in detail (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; this conclusion allows researchers to use the BEMA in future studies.

The EMCA—rated as "Bronze" by Madsen et al. (2017)—was developed by Darren Broder, Michele McColgan, and Rose Finn. This assessment uses 30 multiple-choice items to test basic E&M concepts: Electrostatics, electric fields, circuits, magnetism, and induction. The authors designed the EMCA to be easier than other E&M concept inventories; if the EMCA is used for a pretest, students are able to answer questions and gain confidence about E&M concepts. The EMCA can be used in a pretest-posttest model because the posttest can show mastery at the end of a course (Madsen, McKagan, & Sayre, 2017).

Procedure

This study utilized 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, students were assessed before and after the semester in which students learned Mechanics or Electricity and Magnetism. In Mechanics, students completed the 2015 AP Physics C: Mechanics practice exam, FCI, and MBT assessments; in Electricity and Magnetism, students completed the 2015 AP Physics C: Electricity and Magnetism practice exam, BEMA, and EMCA assessments. During each semester, I implemented Modeling Instruction with AP Physics C: Mechanics or Electricity and Magnetism content (see Appendices A, B, and C for further information). Each unit of content began with a paradigm laboratory, providing an experience for students to create an initial model. Students moved through the Modeling Cycle by performing practice problems and completing more laboratory activities, adding new information to their initial model. Near the end of each unit, students used a whiteboard to summarize their learning into a fully-constructed model; students shared their whiteboards to compare fully-constructed models. Students finished each unit with a written summative assessment containing multiple-choice and short answer problems; some units also had students perform a summative laboratory practicum. The cycle was repeated with a new unit of content, leading to the development of models in Mechanics and Electricity and Magnetism.

In the one-shot case study, student scores were collected from the 2017 AP Physics C: Mechanics and Electricity and Magnetism exams. These assessments occurred at the end of the AP Physics C: Mechanics and Electricity and Magnetism courses, providing a summative assessment of student understanding. The assessments were given during a three-hour block the in the afternoon; students had 1.5 hours for Mechanics and 1.5 hours for Electricity and Magnetism. Each exam consisted of a multiple-choice and free response section, with 45 minutes for each section. Students received a short break after the free response section of Mechanics, returning to complete both sections of the Electricity and Magnetism exam. One student missed the scheduled exam day due to a conflict with an athletic event; this student was assessed during the make-up time block.

Data Analysis

Data was analyzed through a variety of approaches for the one-group pretest-posttest method. For each assessment, simple statistics—mean, median, standard deviation, and range—were calculated. Gains for each student were calculated with two equations: Simple subtraction of the pretest percentage from the posttest percentage; and, the average of gains. The average of gains calculation was created by first calculating the normalized gain for each student, then averaging each student's normalized gain; the equation is $g_{ave} = \langle(Posttest\ \% - Pretest\ \%)\ /\ (100\% - Pretest\ \%)\rangle$ (McKagan, Sayre, & Madsen, 2017). The average of gains is a common measure in PER; in addition, it is a meaningful measure because the researcher can relate individual student gains to the class average gains. Normalized gains have traditional boundaries: Small is defined as less than .30, medium is defined as between .30 and .69, and large is defined as greater than .70 (McKagan et al., 2017).

To visualize relationships between pretest and posttest scores for a single assessment or between posttest scores of two assessments, graphs were created for assessments. The graphs—found in Chapter Four—are the following:

- Posttest Score (%) FCI versus Pretest Score (%) FCI
- Percentage of Students versus Normalized Gain FCI
- Percentage of Students versus Score (%) FCI
- Posttest Score (%) MBT versus Pretest Score (%) MBT

- Pretest Score (%) FCI and Posttest Score (%) FCI versus Pretest Score (%) MBT and Posttest Score (%) MBT
- 2015 AP Physics C: Mechanics: Free Response Score (%) versus Multiple-Choice Score (%)
- 2015 AP Physics C: Mechanics: Number of Students versus AP Exam Score
- Posttest Score (%) BEMA versus Pretest Score (%) BEMA
- Percentage of Students versus Normalized Gain BEMA
- Percentage of Students versus Score (%) BEMA
- Posttest Score (%) EMCA versus Pretest Score (%) EMCA
- Pretest Score (%) BEMA and Posttest Score (%) BEMA versus Pretest Score (%) EMCA and Posttest Score (%) EMCA
- 2015 AP Physics C: Electricity and Magnetism: Free Response Score (%) versus Multiple-Choice Score (%)
- 2015 AP Physics C: Electricity and Magnetism: Number of Students versus AP Exam Score

These calculations and graphs provided a high level of information about student performance in the one-group pretest-posttest method, leading to discussion, implications, and recommendations for future AP Physics C: Mechanics and Electricity and Magnetism courses.

Data was analyzed through several methods in the one-shot case study. Simple statistics—mean, median, standard deviation, and range—were calculated for student scores on the 2017 AP Physics C: Mechanics and Electricity and Magnetism assessments. The College Board provided instructional reports for results on the 2017 AP Physics C:

Mechanics and Electricity and Magnetism assessments, which included a large set of information: Overall score distributions for students in this study and globally; multiple-choice score distributions for students in this study and globally; free response score distributions for students in this study and globally; performance on the multiple-choice section for three content areas; and, performance on the free response section for three content areas. Two graphs are presented, showing the relationship between student scores on the 2017 AP Exam and the posttest of the 2015 AP Practice Exam. These calculations and graphs provide information that shows whether or not Modeling Instruction is a viable pedagogy for teaching AP Physics C: Mechanics and Electricity and Magnetism, leading to discussion, implications, and recommendations for future AP Physics C: Mechanics and Electricity and Magnetism courses.

Plan for Reflecting with Participants on Data

As the students and I progressed through the course, I built trust by sharing information related to models and course sequence. I explained 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 was collected at the end of each course, information was shared with students so they understood how well they did on the assessments. Students reflected on their effort and mental models to consolidate their learning so they could be successful in future science courses.

Plan for Devising an Action Plan

For this study, I identified AP Physics C: Mechanics and Electricity and Magnetism as the area of focus and created a preliminary data collection plan based on previous literature. During the 2016-2017 school year, I collected student background information and scores on assessments, analyzing and interpreting data from these assessments. After interpreting the assessment data, I developed a new action plan for the 2017-2018 school year (see Appendix D for new sequence of models).

Conclusion

This study used an action research design to identify an area of focus, perform a literature review and identify a unique research question, create a plan to test the research question, and analyze data to determine the results of the research question. The study was conducted at a large, successful high school in the southeastern United States; 20 students participated in the Mechanics portion of the study, with 16 students participating in the Electricity and Magnetism part of the study. The problem of practice for this study was to determine the efficacy of Modeling Instruction as a pedagogy for students in AP Physics C: Mechanics and Electricity and Magnetism; the research plan used a one-group pretest-posttest method and one-shot case study to determine the viability of Modeling Instruction as a pedagogy for students in AP Physics C: Mechanics and Electricity and Magnetism. Students received assessments before and after I used Modeling Instruction to teach the AP Physics C content; the extent to which Modeling Instruction is a viable pedagogy is related to student achievement on research-based assessments and the 2017 AP Physics C: Mechanics and Electricity and Magnetism exams. Analysis of the data generates discussion, implications, and recommendations for future AP Physics C: Mechanics and Electricity and Magnetism courses, continuing the action research cycle.

CHAPTER FOUR: Findings from the Data Analysis

This study used an action research paradigm to improve student learning in AP Physics C: Mechanics and Electricity and Magnetism. The problem of practice for this study was to determine the viability of Modeling Instruction as a pedagogy for students in AP Physics C: Mechanics and Electricity and Magnetism; to evaluate this problem of practice, I incorporated Modeling Instruction theory and practice in AP Physics C: Mechanics and Electricity and Magnetism during the 2016-2017 school year. To quantify the viability of Modeling Instruction, I assessed students with a one-group pretest-posttest method and a one-shot case study. For the one-group pretest-posttest method, student scores were collected on the FCI, MBT, BEMA, EMCA, and 2015 AP Physics C: Mechanics and Electricity and Magnetism practice exams. Simple statistics and gains were calculated with student scores on each assessment; this data provides useful information about the viability of Modeling Instruction in AP Physics C. In addition, student scores were graphed to show correlations between pretest and posttest scores for an individual assessment and between posttest scores for multiple assessments. For the one-shot case study, student overall and categorical scores were collected from the 2017 AP Physics C: Mechanics and Electricity and Magnetism Exams. The overall scores and categorical scores were compared to global student scores, providing information about the viability of Modeling Instruction. The collection of information from the data, statistics, and graphs of the one-group pretest-posttest method and one-shot case study supports the discussion, implications, and recommendations in Chapter Five, leading to a determination of the viability of Modeling Instruction in AP Physics C: Mechanics and Electricity and Magnetism.

Findings of the Study

The findings of the study are broken into two sections: Information from the one-group pretest-posttest method and information from the one-shot case study.

One-Group Pretest-Posttest Method: Mechanics

Students performed several assessments in Mechanics for the one-group pretest-posttest method. Students scored highly on the FCI pretest, with a mean of 62%; in comparison with Figure 2.7 (Hestenes, 2006), the FCI pretest means were 26% for Traditional, 26% for Novice Modelers, and 29% for Expert Modelers. The differences between the information in Figure 2.7 and students in this study are large, though this is not surprising given the high level of academic success by students in the study. Students also scored highly on the FCI posttest, with a mean of 79%; in comparison with Figure 2.7 (Hestenes, 2006), the FCI posttest means were 42% for Traditional, 52% for Novice Modelers, and 69% for Expert Modelers. Although students in this study had higher pretest scores, students also had higher posttest scores. However, the raw gain of 17% was lower than the raw gain of the Novice Modeler (26%) and Expert Modeler (40%). The average of the normalized gains was .47, which is within the range defined as medium.

Individual students showed interesting performance on the FCI, especially Students 3, 10, and 15. These students scored 83% on the FCI pretest, which is a high score. On the posttest, Student 3 scored 90%, Student 10 scored 97%, and Student 15 scored 83%.

Table 4.1

Student data on the FCI and MBT

Student	FCI Pretest (%)	FCI Posttest (%)	Raw Gain (%)	Normalized Gain	MBT Pretest (%)	MBT Posttest (%)	Raw Gain (%)	Normalized Gain
1	70	80	10	.33	46	62	16	.30
2	73	90	17	.63	46	62	16	.30
3	83	90	7	.41	54	73	19	.41
4	63	93	30	.81	42	73	31	.53
5	47	77	30	.57	27	54	27	.37
6	43	50	7	.12	46	54	8	.15
7	77	83	6	.26	46	58	12	.22
8	57	77	20	.47	42	54	12	.21
9	60	77	17	.43	46	35	-11	-.20
10	83	97	14	.82	65	85	20	.57
11	57	90	33	.77	50	73	23	.46
12	30	40	10	.14	35	46	11	.17
13	73	77	4	.15	50	62	12	.24
14	50	63	13	.26	42	50	8	.14
15	83	83	0	.00	50	81	31	.62
16	63	97	34	.92	42	85	43	.74
17	70	90	20	.67	54	77	23	.50
18	70	87	17	.57	62	65	3	.08
19	43	63	20	.35	38	54	16	.26
20	43	83	40	.70	38	65	27	.44
Mean	62	79	17	.47	46	63	17	.32
Median	63	83	17	.45	46	62	16	.30
St. Dev.	15	15			9	13		
Min.	30	40			27	35		
Max.	83	97			65	85		
Range	53	57			38	50		

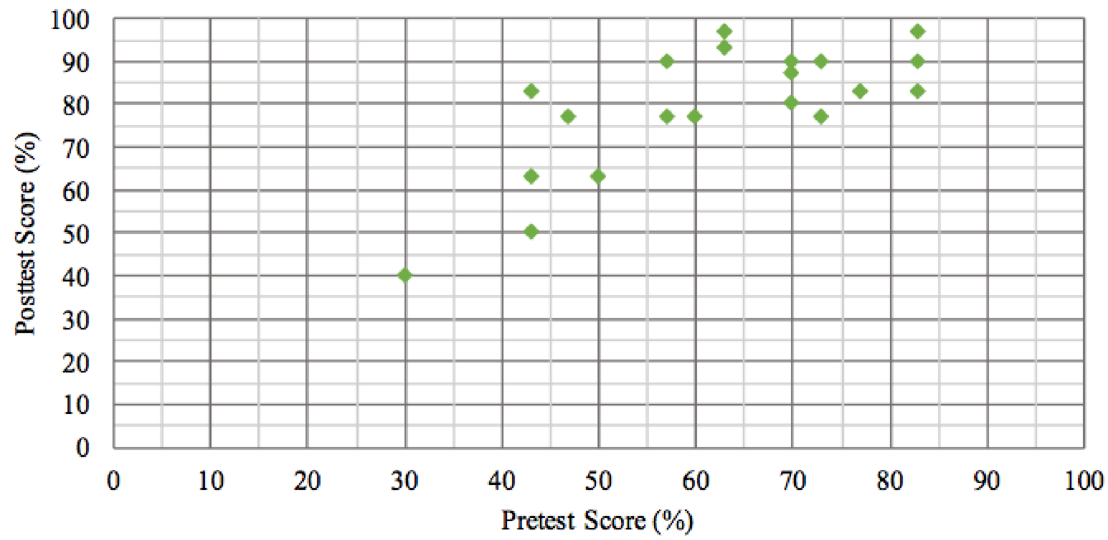

Figure 4.1. Student pretest and posttest scores on the Force Concept Inventory (FCI).

Other students performed less well than their peers on the pretest, though their scores were higher than the average in Figure 2.7: Student 12 scored 30%, and Students 6, 19, and 20 scored 43%. On the posttest, Student 6 scored 50%, Student 12 scored 40%, Student 19 scored 63%, and Student 20 scored 83%. Though Students 6 and 12 had small gains between the pretest and posttest, Students 19 and 20 showed large gains. Figure 4.1 shows a graphical representation of student pretest and posttest scores on the FCI.

Figures 4.2 and 4.3 provide a comparison between students in this study with students in a national database. The American Association of Physics Teachers (AAPT) has compiled student scores from many researchers, allowing researchers to compare class data with national data. Figure 4.2 shows the percentage of students versus normalized gain on the FCI: From the national database, the percentage of students is greatest at no normalized gain and decreases as normalized gain increases; for students in this study, the normalized gain is shifted towards higher gains with the highest percentage of students at a normalized gain of 0.5. Figure 4.3 provides the percentage of students

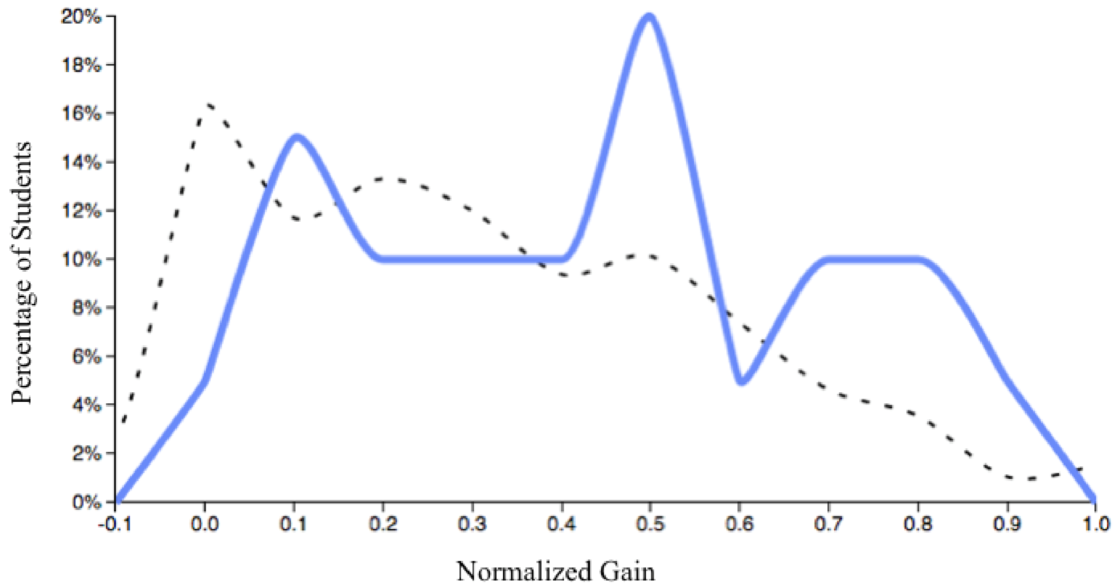

Figure 4.2. Percentage of students versus normalized gain on the FCI. The blue line represents students from this dissertation; the black line represents students in a national database, collected by the American Association of Physics Teachers.

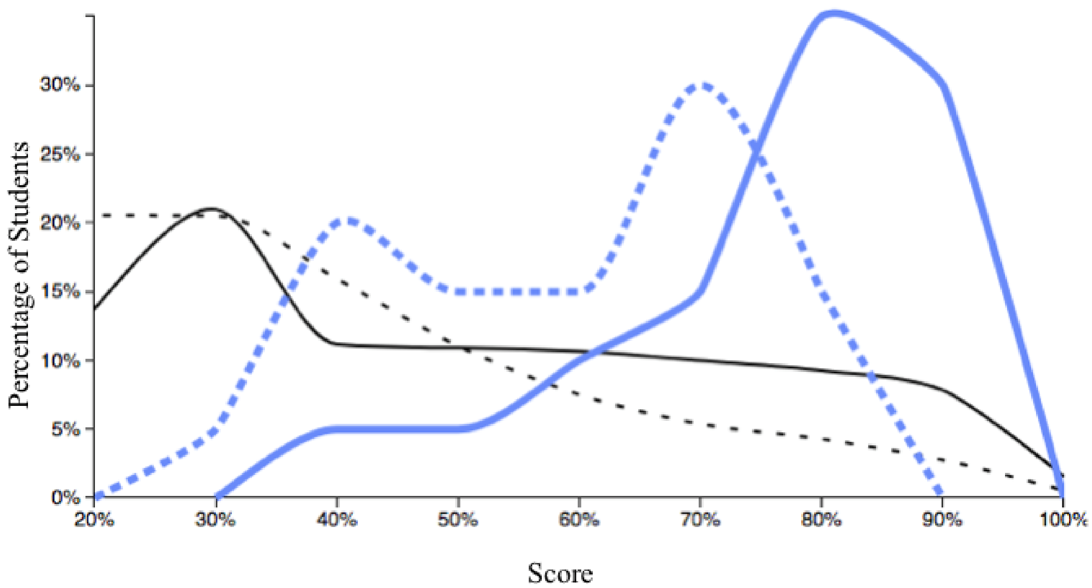

Figure 4.3. Percentage of students versus score on the FCI. The blue lines represent students in this dissertation; the black lines represent students in a national database, collected by the American Association of Physics Teachers. The dashed lines represent scores on the pretest and the solid lines represent scores on the posttest.

versus the score on the FCI. From the national database, approximately 20% of students achieve a score of 30% on the pretest and posttest; the percentage of students decreases as the score increases. Students in this study had a different distribution: On the pretest, approximately 30% of students scored 70%; on the posttest, approximately 35% of students scored between 80% and 90%. These posttest scores indicate a high understanding of forces by many students.

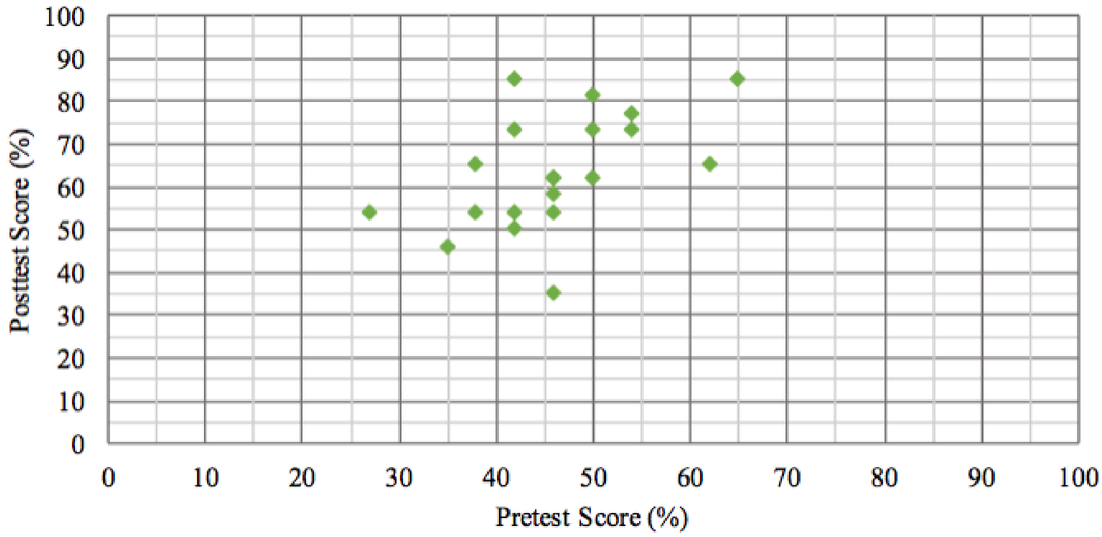

Figure 4.4. Student pretest and posttest scores on the Mechanics Baseline Test (MBT).

On the MBT, students had a mean of 46% on the pretest and 63% on the posttest. These scores have a raw gain of 17% and a normalized gain of .32; this normalized gain is within the ranged defined as medium. Students 10 and 18 had the highest pretest scores, with Student 10 scoring 65% and Student 18 scoring 62%. On the posttest, Students 10, 15, and 16 scored over 80%; Student 10 scored 85%, Student 15 scored 81%, and Student 16 scored 85%. Students 4, 15, and 16 had the highest raw gains: Student 4 had a raw gain of 31%, Student 15 had a raw gain of 31%, and Student 16 had a raw gain of 43%. Figure 4.4 shows a graphical representation of student pretest and posttest scores on the MBT.

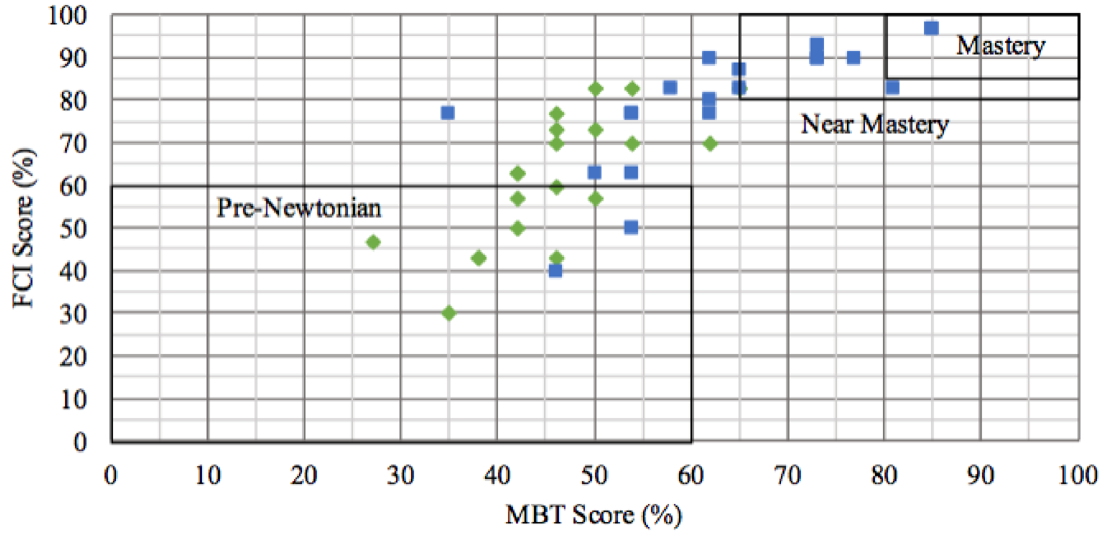

Figure 4.5. Student pretest and posttest scores on the Force Concept Inventory (FCI) and Mechanics Baseline Test (MBT). The green diamonds represent the pretest scores and the blue rectangles represent the posttest scores.

Combining the FCI and MBT data produces a reasonable representation of a student's understanding of mechanics. Wells et al. (1995) define several categories for scores on the FCI and MBT: Pre-Newtonian is defined as scores less than 60% on both the FCI and MBT; Near Mastery is defined as scores between 80% and 85% on the FCI and between 65% and 100% on the MBT; and, Mastery is defined as scores above 85% on the FCI and above 80% on the MBT. With the pretest scores from the FCI and MBT, eight students were in the Pre-Newtonian category; the rest of the students were between Pre-Newtonian and Near Mastery, with no students in the Near Mastery or Mastery categories. Students scored higher on the posttest of the FCI and MBT: Two students were in the Pre-Newtonian category; six students were in the Near Mastery category; and, one student was in the Mastery category. Figure 4.5 shows the pretest and posttest scores on the FCI and MBT.

Table 4.2 provides information on student scores for the 2015 AP Physics C: Mechanics practice exam. Students had a mean of 37% on the pretest of the multiple-choice section, with a mean of 55% on the posttest of the multiple-choice section. The pretest and posttest scores give a raw gain of 18%, with a normalized gain of .28; this normalized gain falls in the small category. Students 2, 10, and 15 scored above 50% on the pretest of the multiple-choice section: Student 2 at 69%, Student 10 at 57%, and Student 15 at 51%. On the posttest of the multiple-choice section, four students scored at or near 70%: Students 4 and 18 scored 69%, with Students 2 and 10 scoring 71%. Students 12 and 20 had the largest raw gain, both with a gain of 31%.

The free response section was more difficult for students because it required students to supply answers; many students left parts of problems blank, especially on the pretest. The mean on the pretest of the free response section was 21% and the mean on the posttest of the free response section was 41%. The pretest and posttest scores give a raw gain of 20% and a normalized gain of .25; this normalized gain falls in the small category. Four students achieved higher than 30% on the pretest of the free response section: Student 2 at 33%, Student 8 at 31%, Student 10 at 33%, and Student 18 at 33%. Two students achieved higher than 65% on the posttest of the free response section, with Student 2 at 69% and Student 16 at 67%. Four students achieved a raw gain over 30%: Student 17 at 35%, Students 1 and 2 at 36%, and Student 16 at 51%. Figure 4.6 provides a graphical representation of student pretest and posttest scores for the multiple-choice and free response sections.

Table 4.2

Student data for each section of the 2015 AP Physics C: Mechanics Practice Exam

Student	Pretest MC (%)	Posttest MC (%)	Raw Gain (%)	Normalized Gain	Pretest FR (%)	Posttest FR (%)	Raw Gain (%)	Normalized Gain
1	31	40	9	.13	11	47	36	.40
2	69	71	2	.06	33	69	36	.54
3	46	63	17	.31	27	40	13	.18
4	43	69	26	.46	27	38	11	.15
5	37	49	12	.19	18	36	18	.22
6	29	34	5	.07	7	27	20	.22
7	31	57	26	.38	11	38	27	.30
8	40	66	26	.43	31	51	20	.29
9	26	49	23	.31	16	18	2	.02
10	57	71	14	.33	33	53	20	.30
11	23	66	43	.56	22	44	22	.28
12	20	51	31	.39	20	29	9	.11
13	31	51	20	.29	11	33	22	.25
14	23	37	14	.18	18	33	15	.18
15	51	43	-8	-.16	27	38	11	.15
16	40	63	23	.38	16	67	51	.61
17	43	63	20	.35	18	53	35	.43
18	46	69	23	.43	33	40	7	.10
19	34	37	3	.05	18	31	13	.16
20	23	54	31	.40	16	27	11	.13
Mean	37	55	18	.28	21	41	20	.25
Median	36	56	20	.32	18	38	19	.22
St. Dev.	13	12			8	13		
Min.	20	34			7	18		
Max.	69	71			33	69		
Range	49	37			26	51		

Table 4.3

Student data of the AP scores on the 2015 AP Physics C: Mechanics Practice Exam

Student	AP Score – Pretest	AP Score – Posttest
1	1	3
2	3	5
3	2	3
4	2	4
5	1	3
6	1	1
7	1	3
8	2	4
9	1	2
10	3	4
11	1	4
12	1	3
13	1	3
14	1	2
15	2	3
16	1	4
17	1	4
18	3	4
19	1	2
20	1	3
Mean	1.50	3.20
Median	1.00	3.00
St. Dev.	0.76	0.95
Min.	1.00	1.00
Max.	3.00	5.00
Range	2.00	4.00

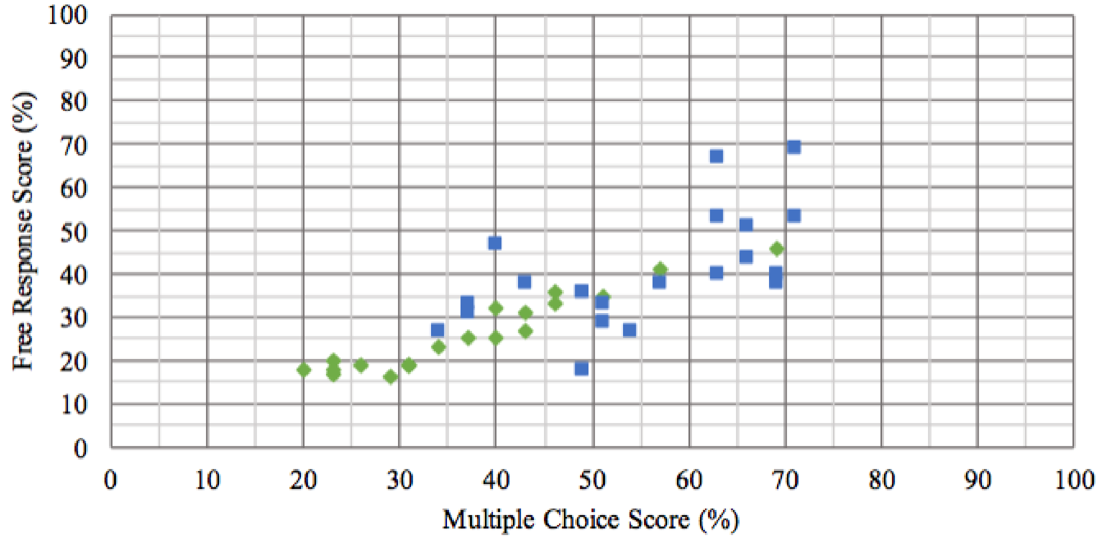

Figure 4.6. Student pretest and posttest scores on the 2015 AP Physics C: Mechanics Practice Exam. The green diamonds represent the pretest scores and the blue squares represent the posttest scores.

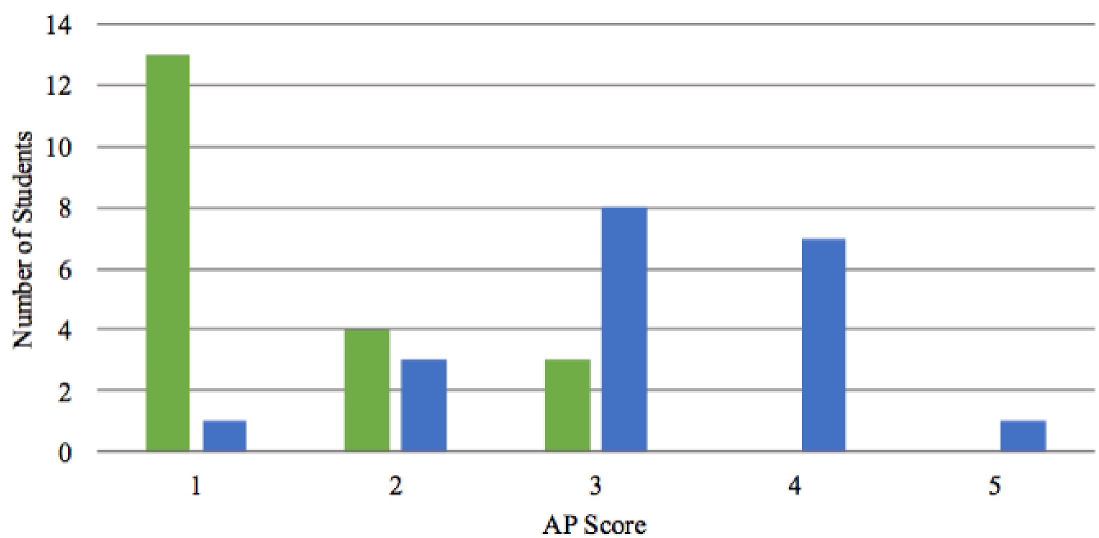

Figure 4.7. Student AP scores on the pretest and posttest for the 2015 AP Physics C: Mechanics Practice Exam. Green bars represent scores on the pretest and blue bars represent scores on the posttest.

Table 4.3 provides information on the overall scores for the 2015 AP Physics C: Mechanics Practice Exam. Students had a pretest mean of 1.50: Thirteen students scored a 1, 4 students scored a 2, 3 students scored a 3, 0 students scored a 4, and 0 students scored a 5. On the posttest, students had a mean of 3.20: One student scored a 1, 3 students scored a 2, 8 students scored a 3, 7 students scored a 4, and 1 student scored a 5. Figure 4.7 shows the number of students at each AP score for the pretest and posttest on the 2015 AP Physics C: Mechanics Practice Exam.

One-Group Pretest-Posttest Method: Electricity and Magnetism

Table 4.4 provides student scores for the BEMA and EMCA. On the BEMA, students had a pretest mean of 25% and a posttest mean of 46%. The pretest and posttest means give a raw gain of 21% and a normalized gain of 27%; this normalized gain is in the small category. On an individual level, no student scored above 40% on the pretest, though four students scored higher than 60% on the posttest: Student 2 at 60%, Student 8 at 70%, Student 13 at 63%, and Student 14 at 73%. Students 8, 13, and 14 had the highest Raw Gains, with Student 8 at 40%, Student 13 at 43%, and Student 14 at 46%. Figure 4.8 provides a graphical representation of student pretest and posttest scores on the BEMA.

Figures 4.9 and 4.10 provide a comparison between students in this study with students in a national database. The American Association of Physics Teachers (AAPT) has compiled student scores from many researchers, allowing researchers to compare class data with national data. Figure 4.9 shows the percentage of students versus normalized gain on the BEMA: From the national database, the percentage of students is greatest at no normalized gain and decreases as normalized gain increases; for students in this study, the normalized gain is shifted towards higher gains with the highest percentage of students at a normalized gain of 0.2. Figure 4.10 provides the percentage of students versus the score on the BEMA. From the national database, approximately 30% of students achieve a score of 20% on the pretest with approximately 17% achieving scores between 30% and 60% on the posttest. Students in this study had a similar distribution as the national distribution on the pretest and posttest, though a higher percentage of students achieved higher scores in this study.

Table 4.4

Student data on the BEMA and EMCA

Student	BEMA Pretest (%)	BEMA Posttest (%)	Raw Gain (%)	Normalized Gain	EMCA Pretest (%)	EMCA Posttest (%)	Raw Gain (%)	Normalized Gain
1	23	50	27	.35	53	73	20	.43
2	37	60	23	.37	50	80	30	.60
3	33	47	14	.21	50	80	30	.60
4	23	37	14	.18	37	63	26	.41
5	30	37	7	.10	27	77	50	.68
6	23	47	24	.31	37	60	23	.37
7	23	33	10	.13	23	40	17	.22
8	30	70	40	.57	50	83	33	.66
9	23	40	17	.22	43	83	40	.70
10	27	40	13	.18	-	-	-	-
11	33	50	17	.25	50	70	20	.40
12	3	27	24	.25	50	67	17	.34
13	20	63	43	.54	37	73	36	.57
14	27	73	46	.63	40	83	43	.72
15	17	40	23	.28	50	67	17	.34
16	33	17	-16	-.24	23	60	37	.48
Mean	25	46	21	.27	41	71	30	.50
Median	25	44	19	.25	43	73	30	.48
St. Dev.	8	15			10	12		
Min.	3	17			23	40		
Max.	37	73			53	83		
Range	34	56			30	43		

Note: Student 10 did not take the EMCA pretest, so no scores or calculations are recorded for any part of the EMCA data.

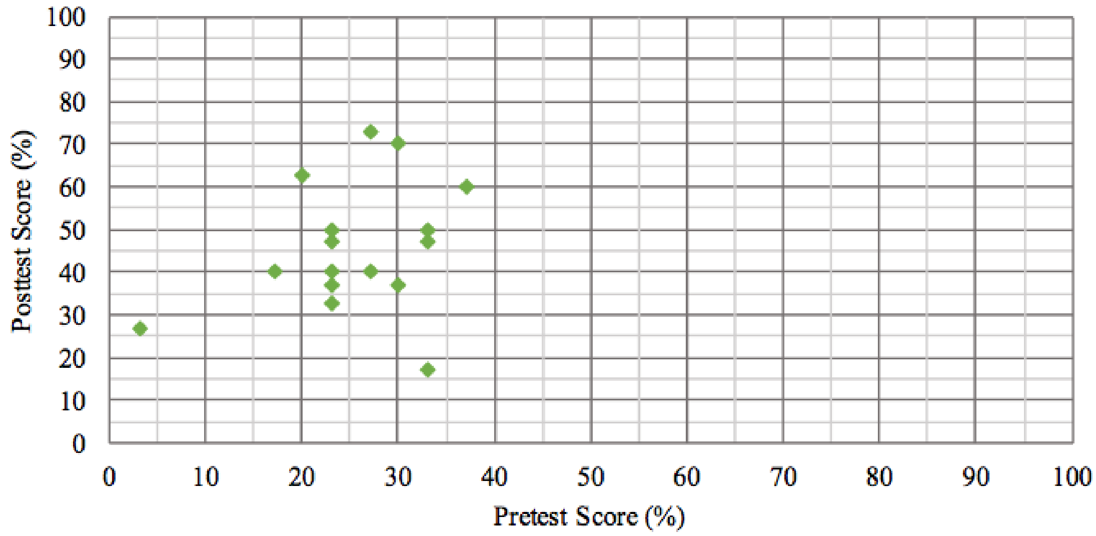

Figure 4.8. Student pretest and posttest scores on the Brief Electricity and Magnetism Assessment (BEMA).

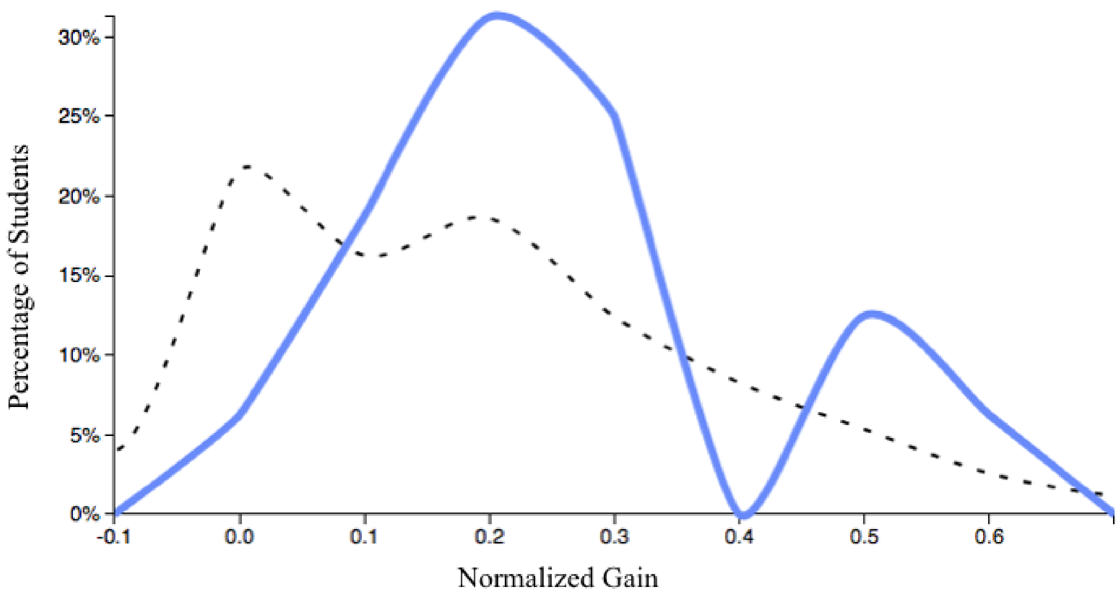

Figure 4.9. Percentage of students versus normalized gain on the BEMA. The blue line represents students from this dissertation; the black line represents students in a national database, collected by the American Association of Physics Teachers.

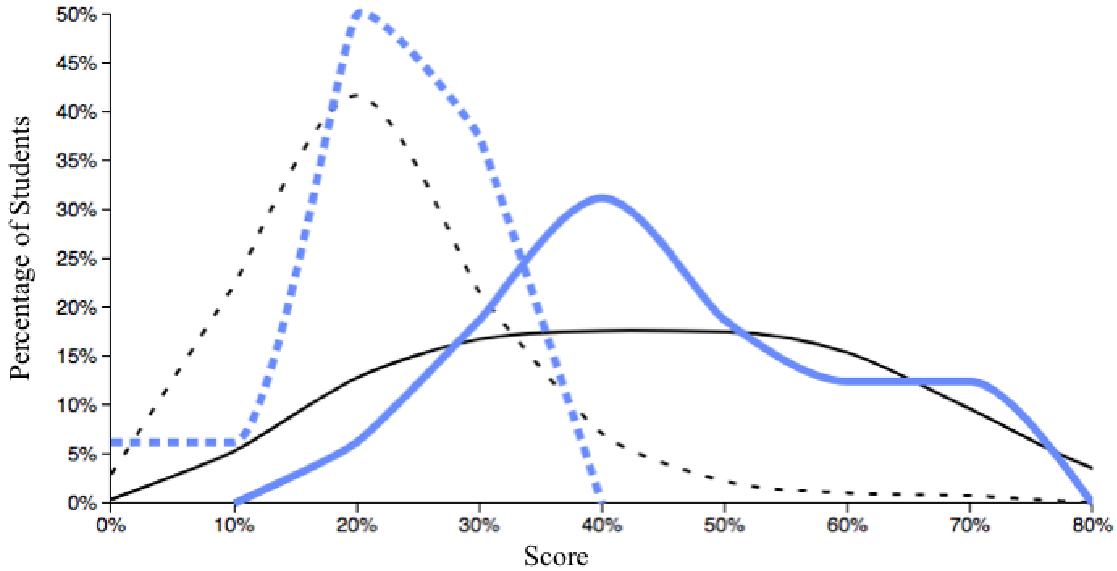

Figure 4.10. Percentage of students versus score on the BEMA. The blue lines represent students in this dissertation; the black lines represent students in a national database, collected by the American Association of Physics Teachers. The dashed lines represent scores on the pretest and the solid lines represent scores on the posttest.

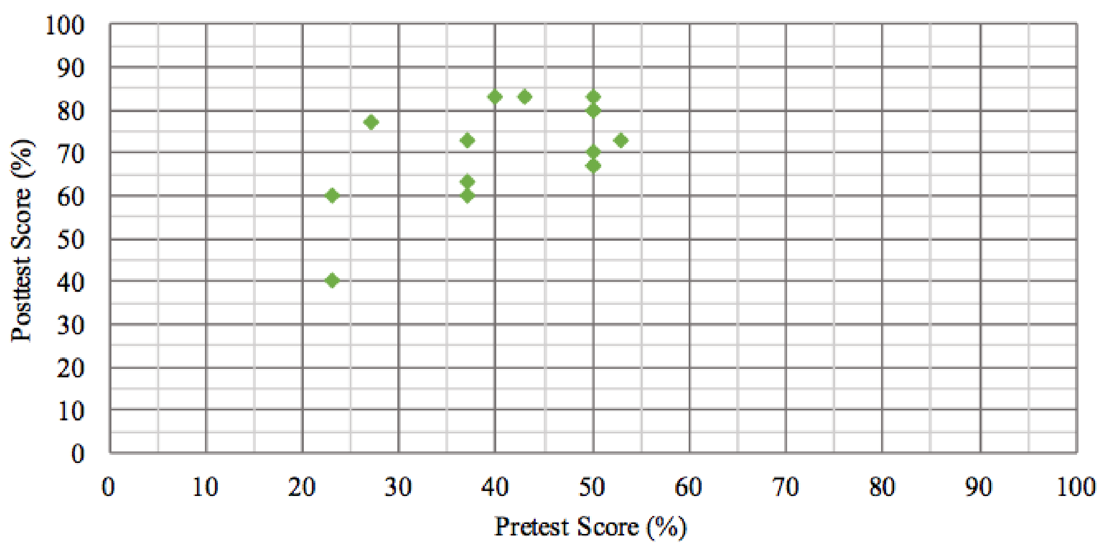

Figure 4.11. Student pretest and posttest scores on the Electricity and Magnetism Conceptual Assessment (EMCA).

On the EMCA, student scores were higher than the BEMA on the pretest and posttest. The EMCA pretest mean was 41% and the posttest mean was 71%. The pretest and posttest means give a raw gain of 30% with a normalized gain of .50; this normalized gain is in the medium category. For individual scores on the EMCA, seven students scored 50% or higher on the pretest: Students 1, 2, 3, 8, 11, 12, and 15. On the posttest, five students scored at or above 80%: Students 2 and 3 at 80%, with Students 8, 9, and 14 at 83%. Three students achieved a raw gain of 40% or greater: Student 9 at 40%, Student 14 at 43%, and Student 5 at 50%. Figure 4.11 provides a graphical representation of student pretest and posttest scores on the EMCA.

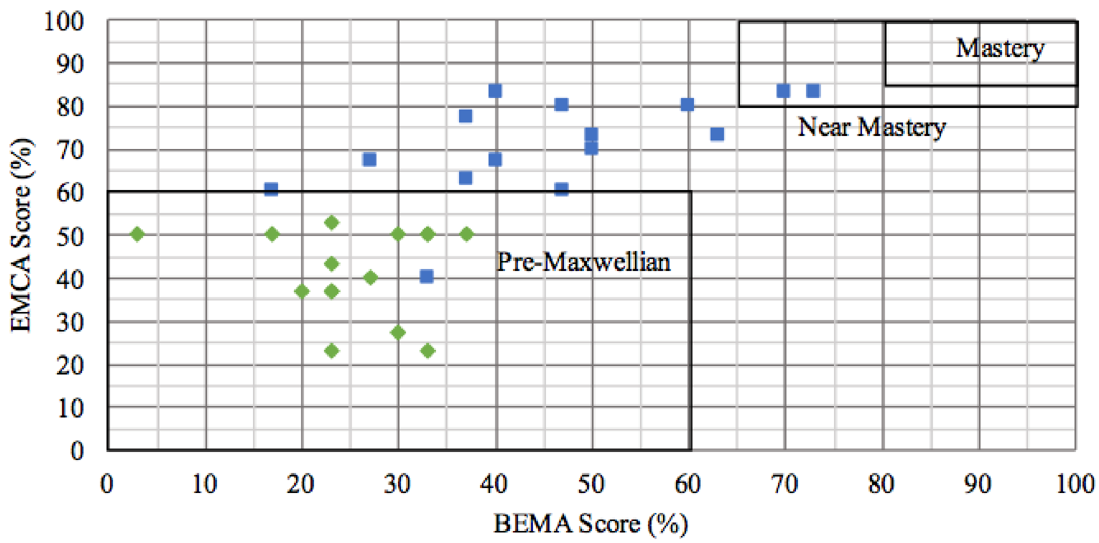

Figure 4.12. Student pretest and posttest scores on the Electricity and Magnetism Conceptual Assessment (EMCA) and Brief Electricity and Magnetism Assessment (BEMA).

Combining the EMCA and BEMA data produces a picture of student understanding on electricity and magnetism topics. I arbitrarily defined three categories for student scores on the EMCA and BEMA, based on the percentages from Wells et al. (1995): Pre-Maxwellian is defined as scores less than 60% on both the EMCA and BEMA; Near Mastery is defined as scores between 80% and 85% on the EMCA and between 65% and 100% on the BEMA; and, Mastery is defined as scores above 85% on the EMCA and above 80% on the BEMA. For the pretest scores, all students scored in the Pre-Maxwellian category; for the posttest scores, one student scored in the Pre-

Maxwellian category, no student scored in the Mastery category, two students scored in the Near Mastery category, and the rest scored outside a designated category. Figure 4.12 provides the scores on the EMCA and BEMA.

Table 4.5 provides student data for the 2015 AP Physics C: Electricity and Magnetism Practice Exam. On the multiple-choice section, Students had a mean pretest score of 29% and a mean posttest score of 43%. The pretest and posttest means have a raw gain of 14% and a normalized gain of .19; this normalized gain is in the small category. Individually, two students scored 37% or higher on the pretest: Student 13 at 40% and Student 16 at 37%. On the posttest, two students scored higher than 50%: Student 1 at 51% and Student 2 at 54%. Four students had a raw gain greater than 20%: Student 1 at 22%, Student 2 at 28%, Student 11 at 23%, and Student 12 at 23%.

On the free response section, students had to supply answers; many students left problems blank, creating low scores for the pretest and posttest. The student pretest mean is 8% and the posttest mean is 24%. The pretest and posttest scores give a raw gain of 16% and a normalized gain of 17%; this normalized gain is in the low category. Individually, no students had a pretest score greater than 20%; however, two students scored approximately 40% on the posttest. Student 2 scored 38% and Student 8 scored 40%; these two students also posted the two highest raw gain increases. Figure 4.13 provides a graphical representation of student pretest and posttest scores for the multiple-choice and free response sections.

Table 4.5

Student data for each section of the 2015 AP Physics C: Electricity and Magnetism Practice Exam

Student	Pretest MC (%)	Posttest MC (%)	Raw Gain (%)	Normalized Gain	Pretest FR (%)	Posttest FR (%)	Raw Gain (%)	Normalized Gain
1	29	51	22	.31	7	22	15	.16
2	26	54	28	.38	11	38	27	.30
3	26	43	17	.23	11	24	13	.15
4	23	34	11	.14	2	9	7	.07
5	29	40	11	.15	7	18	11	.12
6	29	37	8	.11	16	16	0	.00
7	17	31	14	.17	9	20	11	.12
8	31	40	9	.13	11	40	29	.33
9	29	40	11	.15	13	22	9	.10
10	31	40	9	.13	4	29	25	.26
11	26	49	23	.31	7	20	13	.14
12	26	49	23	.31	0	16	16	.16
13	40	46	6	.10	9	33	24	.26
14	34	49	15	.23	11	36	25	.28
15	31	34	3	.04	7	22	15	.16
16	37	49	12	.19	2	16	14	.14
Mean	29	43	14	.19	8	24	16	.17
Median	29	42	12	.16	8	22	15	.15
St. Dev.	5	7			4	9		
Min.	17	31			0	9		
Max.	40	54			16	40		
Range	23	23			16	31		

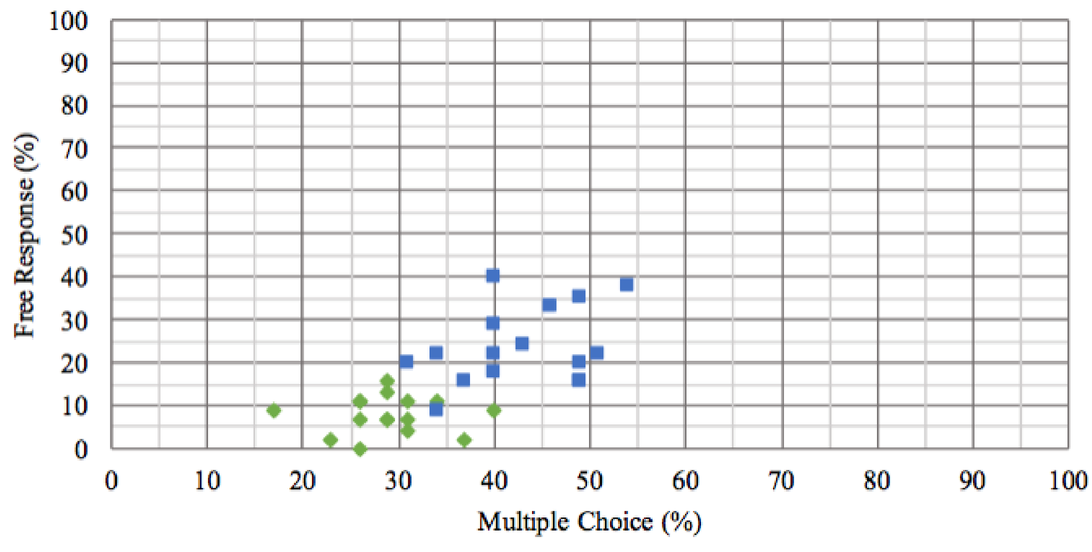

Figure 4.13. Student pretest and posttest scores on the 2015 AP Physics C: Electricity and Magnetism Practice Exam. The green diamonds represent the pretest scores and the blue squares represent the posttest scores.

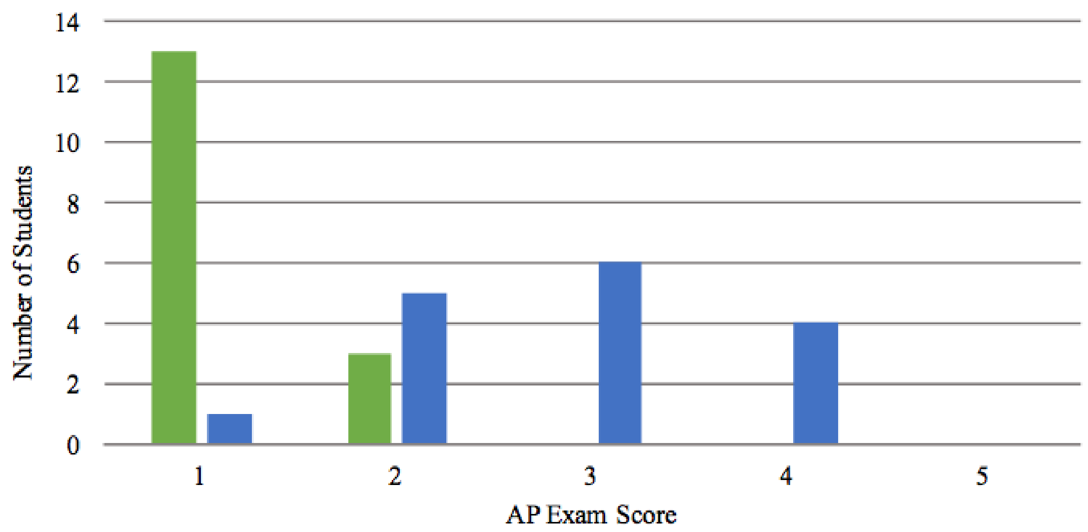

Figure 4.14. Student AP scores on the pretest and posttest for the 2015 AP Physics C: Electricity and Magnetism Practice Exam. Green bars represent scores on the pretest and blue bars represent scores on the posttest.

Table 4.6 provides student data of the AP scores on the 2015 AP Physics C: Electricity and Magnetism Practice Exam. The mean AP score on the pretest is 1.19; three students scored a 2 and the rest scored a 1. The mean AP score on the posttest is

2.81, with a broader distribution of scores. One student scored a 1, 5 students scored a 2, 6 students scored a 3, 4 students scored a 4, and 0 students scored a 5. Figure 4.14 shows the number of students at each AP score for the pretest and posttest on the 2015 AP Physics C: Electricity and Magnetism Practice Exam.

Table 4.6

Student data of the AP scores on the 2015 AP Physics C: Electricity and Magnetism Practice Exam

Student	AP Score – Pretest	AP Score – Posttest
1	1	3
2	1	4
3	1	3
4	1	1
5	1	2
6	2	2
7	1	2
8	1	4
9	1	2
10	1	3
11	1	3
12	1	3
13	2	4
14	2	4
15	1	2
16	1	3
Mean	1.19	2.81
Median	1.00	3.00
St. Dev.	0.40	0.91
Min.	1.00	1.00
Max.	2.00	4.00
Range	1.00	3.00

One-Shot Case Study

For the one-shot case study, student data was collected on the 2017 AP Physics C: Mechanics and Electricity and Magnetism exams. Tables 4.7 and 4.8 provide information about student scores: Table 4.8 describes the number of students achieving scores 1 through 5 on the AP exam; Table 4.7 provides the scores for individual students on each exam. Tables 4.9 and 4.10 provide information about student performance on the multiple-choice and free response sections of the 2017 AP Physics C: Mechanics and Electricity and Magnetism exams: Table 4.9 has information on the Mechanics exam; Table 4.10 has information on the Electricity and Magnetism exam.

Table 4.7 describes the number of students scoring each AP score for both exams; universities and colleges typically award credit for AP scores of 3, 4, or 5, though the credit is dependent on the institution. The College Board (2014) defines a 3 as "Qualified," a 4 as "Well Qualified," and a 5 as "Extremely Well Qualified" (p. 3).

Table 4.7

Number of students for each score on the 2017 AP Physics C: Mechanics and Electricity and Magnetism Exams

AP Score	Number of Students – Mechanics	Number of Students – Electricity and Magnetism
5	2	1
4	10	2
3	3	5
2	4	6
1	1	2

By these definitions, 15 of 20 students were "Qualified" or higher for the Mechanics exam, with 8 of 16 students meeting "Qualified" or higher for the Electricity and

Magnetism exam. Table 4.8 provides information on the AP scores for students on the 2017 AP Physics C: Mechanics and Electricity and Magnetism exams.

Table 4.8

Student data of the overall scores on the 2017 AP Physics C: Mechanics and Electricity and Magnetism Exams

Student	AP Score – Mechanics	AP Score – Electricity and Magnetism
1	4	3
2	5	3
3	4	3
4	4	-
5	3	-
6	2	2
7	2	1
8	4	2
9	2	1
10	4	5
11	4	2
12	1	-
13	3	2
14	3	2
15	4	3
16	5	4
17	4	4
18	4	2
19	2	-
20	4	3
Mean	3.40	2.63
Median	4.00	2.50
St. Dev.	1.10	1.09
Min.	1.00	1.00
Max.	5.00	5.00
Range	4.00	4.00

Note: Students with a missing score in the AP Score – Electricity and Magnetism column had been removed from the Electricity and Magnetism portion of the study.

Table 4.9 provides detailed information about student performance on the 2017 AP Physics C: Mechanics exam. The multiple-choice section has 35 questions; these questions are scaled to represent 45 points. The multiple-choice section is broken into three general content areas: Kinematics; Newton's Laws, Work, Energy, Power; and, Momentum, Rotation, Oscillations, Gravity. The global mean and students-in-study mean represent the number of correct questions in each content area; the number of correct questions is scaled to give a summary score. The global mean score was 23 of 45, though students in this study scored 21 of 45.

Table 4.9

Student performance on the 2017 AP Physics C: Mechanics Exam

Multiple-Choice Section (Maximum Possible Score = 45)			
Content Area	Number of Questions	Global Mean	Students-in-Study Mean
Kinematics	6	3	3
Newton's Laws, Work, Energy, Power	13	7	6
Momentum, Rotation, Oscillations, Gravity	16	8	7
Summary		23	21
Free Response Section (Maximum Possible Score = 45)			
Question/Problem	Max Possible Score	Global Mean	Students-in-Study Mean
Newton's Laws; Kinematics	15	6.3	3.5
Energy; Newton's Laws; Kinematics	15	5.2	4.3
Rotation; Energy; Kinematics	15	5.4	4.9
Summary		16.9	12.7

Note: Adapted from the Instructional Planning Report provided by the College Board.

The free response section is broken into content areas on each problem: Problem 1 had Newton's Laws and Kinematics; Problem 2 had Energy, Newton's Laws, and Kinematics; and, Problem 3 had Rotation, Energy, and Kinematics. The global mean and students-in-study mean represent the number of points on each problem; each problem is worth a maximum of 15 points. The global mean was 16.9 of 45, with students in this study having a mean of 12.7.

Table 4.10 provides detailed information about student performance on the 2017 AP Physics C: Electricity and Magnetism exam. The multiple-choice section has 35 questions; these questions are scaled to represent 45 points.

Table 4.10

Student performance on the 2017 AP Physics C: Electricity and Magnetism Exam

Multiple-Choice Section (Maximum Possible Score = 45)			
Content Area	Number of Questions	Global Mean	Students-in-Study Mean
Electrostatics, Conductors, Capacitors	14	6	5
Electric Circuits	8	4	4
Magnetostatics, Electromagnetism	13	6	5
Summary		22	17
Free Response Section (Maximum Possible Score = 45)			
Question/Problem	Max Possible Score	Global Mean	Students-in-Study Mean
Electrostatics; Conductors/Capacitors	15	3.7	1.5
Circuits	15	5.3	4.3
Magnetostatics	15	6.4	5.4
Summary		15.5	11.2

Note: Adapted from the Instructional Planning Report provided by the College Board.

The multiple-choice section is broken into three general content areas: Electrostatics, Conductors, Capacitors; Electric Circuits; and, Magnetostatics, Electromagnetism. The global mean and students-in-study mean represent the number of correct questions in each content area; the number of correct questions is scaled to give a summary score. The global mean score was 22 of 45, though students in this study scored 17 of 45. The free response section is broken into content areas on each problem: Problem 1 had Electrostatics, Conductors/Capacitors; Problem 2 had Circuits; and, Problem 3 had Magnetostatics. The global mean and students-in-study mean represent the number of points on each problem; problems are worth a maximum of 15 points. The global mean was 15.5 of 45, with students in this study having a mean of 11.2.

Interpretation of Results of the Study

The data collection and analysis for this study produced six tables of information for the one-group pretest-posttest method and four tables of information for the one-shot case study, with figures accompanying the information. This section discusses an interpretation of results for the one-group pretest-posttest method and one-shot case study, providing information to determine the viability of Modeling Instruction in AP Physics C: Mechanics and Electricity and Magnetism.

One-Group Pretest-Posttest Method: Mechanics

In the Mechanics section, 20 students were assessed using the FCI, MBT, and 2015 AP Physics C: Mechanics Practice Exam. On the FCI, students had a pretest mean of 62% and a posttest mean of 79%; both means are high, especially the pretest mean. Although 7 of the 20 students had not completed a prior physics course, a pretest mean of 62% demonstrated that students had a high level of background knowledge on forces. Students increased their understanding of forces throughout the mechanics class. Based on previous literature (Jackson et al., 2008), the posttest mean of 79% is high. On the MBT, students had a pretest mean of 46% and a posttest mean of 63%; the moderately-high pretest mean showed that students had some prior understanding of mechanics. Students increased their understanding of mechanics throughout the course, as seen by the increased posttest mean. Combining the FCI and MBT data for each student produced a profile of mechanics understanding; from the pretest to the posttest, all students increased their FCI scores and 19 of 20 students increased their MBT scores. Students increased "categories" from pretest to posttest: The number of students in the Pre-Newtonian category dropped from eight students with the pretest scores to two students with the posttest scores; the number of students in the Near Mastery category went from zero with the pretest scores to six with the posttest scores; and, the number of students in the Mastery category went from zero with the pretest scores to one with the posttest scores. This increase in student scores on the FCI and MBT demonstrated an increase in student understanding of mechanics, leading to positive outcomes on 2017 AP Physics C: Mechanics Exam.

On the 2015 AP Physics C: Mechanics Practice Exam, students performed poorly on the pretest and relatively well on the posttest. The Practice Exam has two parts: On the multiple-choice section, the pretest mean was 37% and the posttest mean was 55%; on the free response section, students scored a pretest mean of 21% and a posttest mean of 41%. Combining the multiple-choice and free response parts gave an AP score for each student: On the pretest, 3 students achieved a score of 3 or higher; on the posttest, 16 students achieved a score of 3 or higher. The pretest means were low because students had a low amount of background knowledge on rotation and oscillations; these topics were not covered in-depth during prior physics courses. In addition, the Practice Exam had questions requiring knowledge of calculus to complete; most students were co-enrolled in a calculus course and did not have enough background knowledge. The posttest means were higher for each section because students went through the Modeling

Cycle for each set of Mechanics content. Through their calculus course and in AP Physics C, students gained knowledge of calculus; this knowledge helped with problems that required differentiation, integration, or the creation of a differential equation. These scores demonstrate that students understood the Mechanics content, providing evidence that Modeling Instruction is a viable method for teaching.

One-Group Pretest-Posttest Method: Electricity and Magnetism

In the Electricity and Magnetism section, 16 students were assessed with the BEMA, EMCA, and 2015 AP Physics C: Electricity and Magnetism Practice Exam. Students had difficulties with the BEMA, scoring a pretest mean of 25% and a posttest mean of 46%. The low pretest scores show a lack of background knowledge on the concepts embedded in the BEMA; this is to be expected because many of these topics were absent from previous physics courses. Though the posttest mean seems low, student scores were approximately the same distribution as the national average. The BEMA is a difficult assessment for any level student, especially for students who were studying Electricity and Magnetism for the first time. On the EMCA, students performed better, with a pretest mean of 41% and a posttest mean of 71%. This assessment was designed to be easier than other electricity and magnetism assessments (Madsen et al., 2017), which is reinforced by data from this study. Combining the BEMA and EMCA data for each student produced a profile of electricity and magnetism understanding; from the pretest to the posttest, 15 of 16 students increased their BEMA and all students increased their EMCA scores. Students increased categories from pretest to posttest: The number of students in the Pre-Maxwellian category dropped from 16 students with the pretest scores to 3 students with the posttest scores; the number of students in the Near Mastery category went from 0 with the pretest scores to 2 with the posttest scores. No student reached the Mastery category with the pretest or posttest scores, largely due to difficulties on the BEMA. Though students increased from pretest score to posttest score, the gains were moderate; these moderate gains correlate with the moderate success on the 2017 AP Physics C: Electricity and Magnetism Exam.

On the 2015 AP Physics C: Electricity and Magnetism Practice Exam, students scored poorly on all sections. The Practice Exam has two parts: On the multiple-choice section, the pretest mean was 29% and the posttest mean was 43%; on the free response section, students scored a pretest mean of 8% and a posttest mean of 24%. Students scored much lower on the free response than the multiple-choice because the free response questions were supply-response; if students could not answer a question, then students had to leave the question blank. Combining the multiple-choice and free response parts gave an AP score for each student: On the pretest, 0 students achieved a score of 3 or higher; on the posttest, 10 students achieved a score of 3 or higher. The pretest means are low because students have a limited amount of background knowledge; many students left large portions of the free response questions blank. Students achieved higher scores on the posttest of each section, though scores were still low. One reason is that Electricity and Magnetism are difficult subjects for many students, especially when students must combine advanced mathematics techniques with new physics concepts. Students were developing their calculus knowledge throughout the electricity and magnetism section; in addition, students learned and applied mathematical techniques for three-dimensional vectors. Students had not learned these techniques in any previous mathematics courses, causing further confusion for students.

One-Shot Case Study

Students performed reasonably well on the 2017 AP Physics C: Mechanics Exam, with 15 of 20 students scoring of 3 or higher. Of the 15 students scoring 3 or higher, 10 students achieved a score of 4 and 2 students attained a score of 5. On the multiple-choice section, students had a mean of 21 points of a possible 45 points; this mean is close to the global mean of 23 points of a possible 45 points. On the free response section, the students in this study had mean that was lower than the global mean; the global mean was 16.9 points of a possible 45 points, but students in this study had a mean of 12.7 points of a possible 45 points. Students in this study struggled with Problem 1, which focused on Newton's Laws and Kinematics. The global mean for Problem 1 was 6.3 points from 15 possible points, but students in this study had a mean of 3.5 points of a possible 15 points. For Problems 2 and 3, students in this study had a mean slightly below the global mean for each problem.

Students performed moderately on the 2017 AP Physics C: Electricity and Magnetism Exam, with 8 of 16 students scoring 3 or higher. Of the eight students who scored 3 or higher, two students achieved a score of 4 and one student achieved a score of 5. On the multiple-choice section, the global mean was 22 points of a possible 45 points; students in this study had a mean of 17 points of a possible 45 points. Students had difficulties with two sections: Electrostatics, Conductors, Capacitors; and, Magnetostatics, Electromagnetism. On each section, the global mean was higher than the mean of students in this study. For the free response section, the global mean was 15.5 points of a possible 45 points; students in this study had a mean of 11.2 points of a possible 45 points. Problem 1 focused on Electrostatics and Conductors/Capacitors;

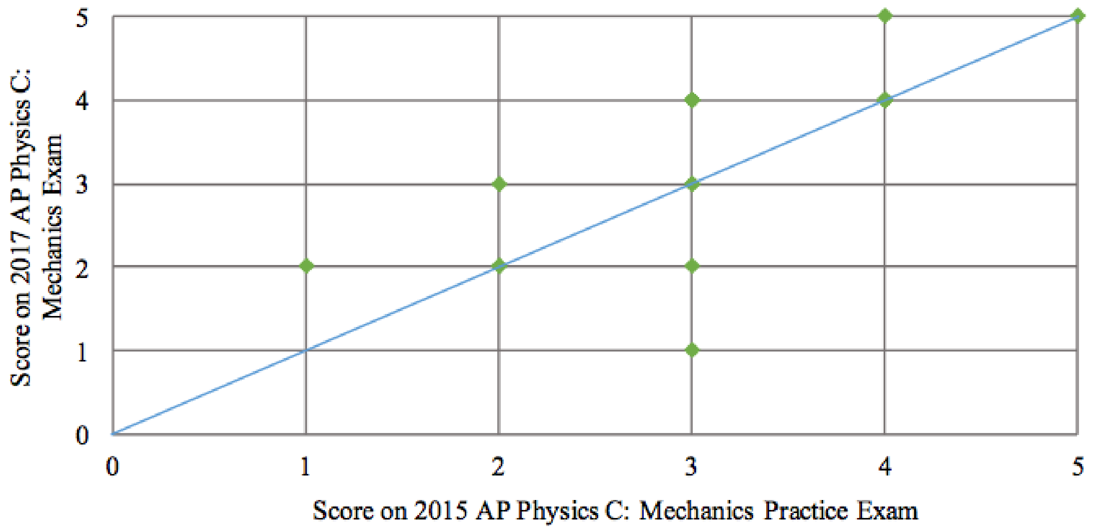

Figure 4.15. Student AP scores on the 2015 AP Physics C: Mechanics Practice Exam and 2017 AP Physics C: Mechanics Exam. The blue line represents a one-to-one ratio between the exams: Students with scores below the line scored lower on the 2017 Exam than the 2015 Exam; students with scores on the line scored the same on the exams; and, students with scores above the line scored higher on the 2017 Exam than the 2015 Exam.

students greatly struggled with this problem, having a mean of 1.5 points of a possible 15 points. Students had higher means on Problems 2 and 3, though the mean of students in this study was lower than the global mean.

Though Practice Exams are not predictive, it was interesting to compare scores between the 2015 AP Physics C: Mechanics Practice Exam and 2017 AP Physics C: Mechanics Exam. From the 2015 Practice Exam to the 2017 Exam, 18 of 20 students scored the same or higher: 11 students had the same score on both exams and 7 students increased their score. Figure 4.15 provided a graphical representation of this data. Scores on the 2017 Exam demonstrated that many students had an acceptable understanding of Mechanics, showing that students can succeed in AP Physics C: Mechanics with Modeling Instruction. From the 2015 AP Physics C: Electricity and Magnetism Practice Exam to the 2017 AP Physics C: Electricity and Magnetism Exam, 11 of 16 students scored the same or higher: 9 students had the same score on both exams; 2 students

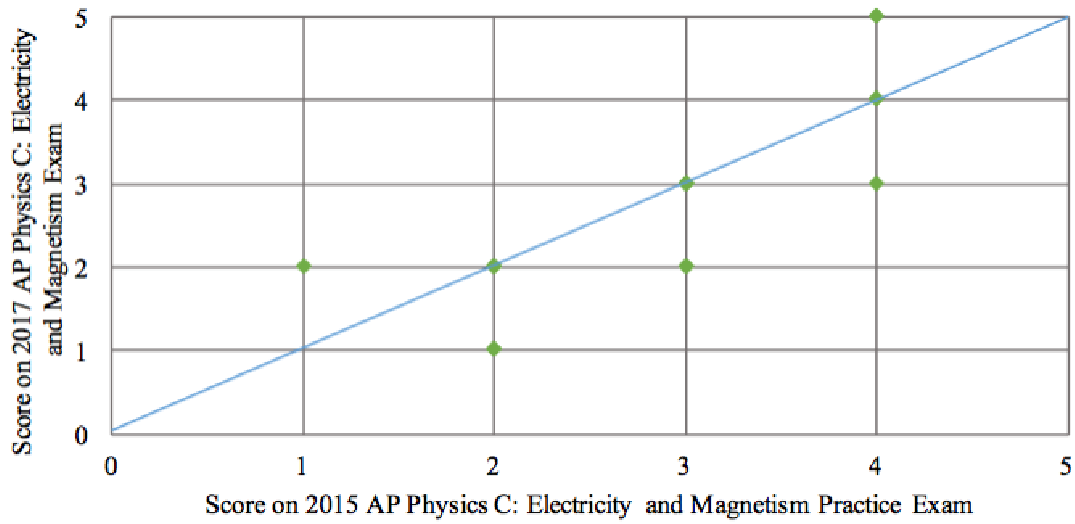

Figure 4.16. Student AP scores on the 2015 AP Physics C: Electricity and Magnetism Practice Exam and 2017 AP Physics C: Electricity and Magnetism Exam. The blue line represents a one-to-one ratio between the exams: Students with scores below the line scored lower on the 2017 Exam than the 2015 Exam; students with scores on the line scored the same on the exams; and, students with scores above the line scored higher on the 2017 Exam than the 2015 Exam.

increased their score. Figure 4.16 provided a graphical representation of this data. These scores provided inconclusive evidence about the viability of Modeling Instruction in AP Physics C: Electricity and Magnetism.

Conclusion

Students were assessed using a one-group pretest-posttest method and one-shot case study to determine the viability of Modeling Instruction in AP Physics C: Mechanics and Electricity and Magnetism. Within the one-group pretest-posttest method, students performed well on the Mechanics assessments but performed moderately on the Electricity and Magnetism assessments. For the one-shot case study, students performed reasonably well on the 2017 AP Physics C: Mechanics Exam and moderately on the 2017 AP Physics C: Electricity and Magnetism Exam. These results provide evidence that

Modeling Instruction is a viable pedagogy in Mechanics, though results in Electricity and Magnetism question the viability of the Modeling Instruction pedagogy.

CHAPTER FIVE: Discussion, Implications, and Recommendations

This study used an action research paradigm to improve my teaching in AP Physics C: Mechanics and Electricity and Magnetism. The problem of practice for this study was to determine the viability of Modeling Instruction as a pedagogy for students in AP Physics C: Mechanics and Electricity and Magnetism; to evaluate this problem of practice, I incorporated Modeling Instruction theory and practice in AP Physics C: Mechanics and Electricity and Magnetism during the 2016-2017 school year. To quantify the viability of Modeling Instruction, I assessed students with a one-group pretest-posttest method and a one-shot case study. For the one-group pretest-posttest method, student scores were collected on the FCI, MBT, BEMA, EMCA, and 2015 AP Physics C: Mechanics and Electricity and Magnetism practice exams. Simple statistics and gains were calculated with student scores on each assessment; this data provided useful information about the viability of Modeling Instruction in AP Physics C. In addition, student scores were graphed to show correlations between pretest and posttest scores for an individual assessment and between posttest scores for multiple assessments. For the one-shot case study, student overall and categorical scores were collected from the 2017 AP Physics C: Mechanics and Electricity and Magnetism Exams. The overall scores and categorical scores were compared to global student scores, providing information about the efficacy of Modeling Instruction.

Overview/Summary of the Study

The general purpose of the study related to the viability of Modeling Instruction as a pedagogy in AP Physics C. Chapter Two provided information on several topics: The development of science pedagogy from the 1800s to Modeling Instruction, demonstrating that Modeling Instruction is the next development of science pedagogy; constructivism and the Modeling Theory of Cognition, with additional references to cognitive linguistics and philosophy embedded in the Modeling Theory of Cognition; and, the foundational aspects of Modeling Instruction, with connections between modern views of learning and Modeling Instruction. Chapter Three discussed the action research methodology to collect data; Chapter Four presented the data and analysis, with discussion about the viability of Modeling Instruction in AP Physics C: Mechanics and Electricity and Magnetism. Appendices A through D described information about the models used during the study; these models were updated to include content specific to AP Physics C: Mechanics and Electricity and Magnetism. In addition to describing information about models, Appendix B provided a standardized method for presenting a model. Information from the specific purposes contributes to the knowledge base within PER, advancing research on the topics of AP Physics C: Mechanics and Electricity and Magnetism and Modeling Instruction.

Major Points from the Study

In an attempt to determine the viability of Modeling Instruction as a pedagogy in AP Physics C: Mechanics and Electricity and Magnetism, research results were combined from the one-group pretest-posttest method and summarized in Table 5.1. According to McKagan, Sayre, & Madsen (2017), normalized gains have traditional boundaries: Small is defined as less than .30, medium is defined as between .30 and .69, and large is defined as greater than .70.

Table 5.1

Raw gain and normalized gain for assessments

Assessment	Raw Gain	Normalized Gain
FCI	17%	.47 Medium
MBT	17%	.32 Medium
2015 Mechanics Practice Exam: Multiple-Choice	18%	.28 Small
2015 Mechanics Practice Exam: Free Response	20%	.25 Small
BEMA	21%	.27 Small
EMCA	30%	.50 Medium
2015 Electricity and Magnetism Practice Exam: Multiple-Choice	14%	.19 Small
2015 Electricity and Magnetism Practice Exam: Free Response	16%	.17 Small

For Mechanics, students showed moderate gains between the pretest and posttest: On the FCI, students had a raw gain of 17% and a normalized gain of .47 (medium category); on the MBT, students had a raw gain of 17% and a normalized gain of .32 (border of small and medium categories); on the multiple-choice section of the 2015 AP Physics C: Mechanics Practice Exam, students had a raw gain of 18% and normalized gain of .28 (border of small and medium categories); and, on free response section of the 2015 AP Physics C: Mechanics Practice Exam, students had a raw gain of 20% and normalized gain of .25 (small category). When student scores were combined on the FCI and MBT, students showed an increased understanding of mechanics by moving from the Pre-Newtonian area to the Near Mastery and Mastery areas. Students performed well on the 2017 AP Physics C: Mechanics Exam; 15 of 20 students scored a 3 or higher. Though quantitative results must be interpreted cautiously due to a low number of students in the study, the results suggest that Modeling Instruction is a viable pedagogy for use in AP Physics C: Mechanics.

For Electricity and Magnetism, students showed moderate gains between the pretest and posttest: On the BEMA, students had a raw gain of 21% and a normalized gain of .27 (border of small and medium categories); on the EMCA, students had a raw gain of 30% and a normalized gain of .50 (medium category); on multiple-choice section of the 2015 AP Physics C: Electricity and Magnetism Practice Exam, students had a raw gain of 14% and a normalized gain of .19 (small category); and, on the free response section of the 2015 AP Physics C: Electricity and Magnetism Practice Exam, students had a raw gain of 16% and a normalized gain of .17 (small category). When student scores were combined on the BEMA and EMCA, students showed an increased understanding of electricity and magnetism by moving out of the Pre-Maxwellian area; however, two students scored in the Near Mastery area and no students scored in the Mastery area. Students performed moderately well on the 2017 AP Physics C: Electricity and Magnetism Exam; 8 of 16 students scored a 3 or higher. The results suggest that Modeling Instruction is a potentially viable pedagogy for use in AP Physics C: Electricity and Magnetism; however, I must better implement Modeling Instruction in future courses.

Action Plan: Implications of the Findings of the Study

Because an action plan is cyclical, the end of one action plan begets the beginning of another action plan. This study represented my second attempt to incorporate Modeling Instruction into AP Physics C: Mechanics and Electricity and Magnetism. In both sections of the course during the 2017-2018 school year, I plan to make modifications based on these results. For the Mechanics section, the order of models will change to incorporate rotational ideas earlier into the course. Students struggled with the Rigid Body Rotational model during this study, so this model will be broken into smaller models; the new rotation models will follow relevant linear models, allowing students to understand similarities and differences between linear and rotational models. See Appendix D for the order of models during the 2017-2018 school year.

For the Electricity and Magnetism section, I noticed several areas that require improvement. Students have less familiarity with foundational electricity and magnetism concepts, so students need more guidance during all laboratory activities. Students became lost—especially during the paradigm lab—and were unable to connect the laboratory activity to the theoretical concept; this breakdown severely limits the amount of understanding for a concept. Students also have difficulties with mathematics; to fully understand some electricity and magnetism concepts, students need to have fluency with three-dimensional vector mathematics. Almost no students have studied dot products, cross products, or closed-loop integrals in their current or prior mathematics courses; this lack of background knowledge slows the learning process because students must learn both the mathematics and physics concepts. I will provide more guidance on the mathematics and physics concepts to remedy these issues, focusing on moving students through the Modeling Cycle to develop a robust model.

For Mechanics and Electricity and Magnetism, I will assess students with problems that focus on a specific model. During this study, students solved problems from the textbooks and prior AP exams; these are good problems for general problem-solving, but the focus was calculating a correct answer. To help students develop a modeling-centric approach to science, students should solve problems that have an emphasis on models and modeling; I will create problems that compel students to use multiple representations to develop a solution. These problems will be in multiple formats, with some problems requiring written solutions and others requiring a laboratory solution. Students will continue to practice prior AP problems; however, rather than focusing on pure computation, students will emphasize models and modeling.

Suggestions for Future Research

Because this study was the first to incorporate Modeling Instruction in AP Physics C: Mechanics and Electricity and Magnetism, future research could progress in many areas. Researchers could develop studies that provide evidence about types of mental models, generating experimental and theoretical advances in the Modeling Theory of Cognition. Researchers could also find teachers with more experience in Modeling Instruction, leading to a better implementation of Modeling Instruction in AP Physics C: Mechanics and Electricity and Magnetism. Researchers could perform a comparative study between many teachers of AP Physics C: Mechanics and Electricity and Magnetism, determining the relative efficacy of different types of pedagogies. Also, a study of teachers who implement Modeling Instruction in AP Physics C: Mechanics and

Electricity and Magnetism with different student populations might yield important information. These populations would include students with different ethnicities, socioeconomic status, gender, or prior physics knowledge. Finally, incorporating qualitative methods—interviews, problem-solving think-aloud, or diagramming whole-class discussions—could provide a richer understanding of student learning, offering more context to explain student learning and processing. By triangulating this information with quantitative measures, researchers might gain a holistic view of Modeling Instruction as a pedagogy in AP Physics C: Mechanics and Electricity and Magnetism.

Conclusion

This study was unique in the PER literature, connecting Modeling Instruction with AP Physics C: Mechanics and Electricity and Magnetism. The information provided in this paper shared the following: The development of science pedagogy from the 1800s to Modeling Instruction; the connection of constructivism with the Modeling Theory of Cognition; foundational aspects of Modeling Instruction, connecting modern views of learning with Modeling Instruction; methodology, data, and analysis to determine the viability of Modeling Instruction as a pedagogy in AP Physics C; models for content in AP Physics C; and, a standardized method of describing a model. Though students performed moderately on assessments in the one-group pretest-posttest method and one-shot case study, this study demonstrated that Modeling Instruction is a viable pedagogy for AP Physics C: Mechanics and Electricity and Magnetism overall. As a science educator, this study helped me understand the power of action research, harnessing the cyclical nature of action research to improve the understanding of Modeling Instruction.

The results of the study offer important insight to further develop the pedagogical approach in my classroom within the next school year. Beyond how the results will be used in my classroom, the study illustrates that Modeling Instruction in AP Physics C: Mechanics and Electricity and Magnetism warrants further exploration and has the potential to be of interest to other practitioners.

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APPENDIX A – SEQUENCE OF MODELS IN AP PHYSICS C FOR 2016-2017

This was the sequence of models in AP Physics C followed during the 2016-2017 school year. For detailed information of each model, see Appendix B. For connections between each model and learning objectives from the College Board (2014), see Appendix C. For information regarding the sequence of models for 2017-2018, see Appendix D.

Mechanics:

1. Constant Velocity Particle Model
2. Uniform Acceleration Particle Model
3. Balanced Force Model
4. Impulsive-Force and Conservation of Momentum Model
5. Unbalanced Force Model
6. Constant Angular Velocity Particle Model
7. Constant Angular Acceleration Particle Model
8. Central Net Force Model
9. Energy Storage and Transfer Model
10. Rigid Body Rotational Model
11. 2-D Motion Model
12. Harmonic Motion Model
13. Gravitation 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

This is a description of the models in AP Physics C: Mechanics and Electricity and Magnetism; information has been adapted from AMTA (2017a) Modeling Curriculum Resources.

Definitions:

- Model: Representation of structure in a given system
- System: Set of related objects, which may be real or imaginary, physical or mental, simple or composite
- Structure: Set of relations among its objects

Parts of a Model:

- Descriptions:
    - Object Description:
        - Type
        - Composition
        - Object variables – Represent intrinsic properties of the object have fixed values
    - Process Description:
        - Reference system
        - State variables – Represent intrinsic properties with values that may vary with time; a descriptor regarded as state variables in one model may be an object variable in another model
        - Often useful to use graphical methods
    - Interaction Description:
        - Type and agent
        - Interaction variables – Represents the interaction of some external object (called an agent) with the object being modeled
        - Often useful to use diagrams
- Formulations:
    - Dynamical Laws – Mathematical equation(s) that determine(s) the time evolution of state variables
    - Interaction Laws – Mathematical equation(s) that express(es) interaction variables as functions of state variables
- Ramifications:
    - Linguistic – Written and verbal communication about the system and structure
    - Computational – Use of a computer program to encode the system and structure

Information:

- 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.

Mechanics:

1. Constant Linear Velocity Particle Model
    a. Descriptions:
        i. Object Description
            1. Object variable
                a. Velocity
        ii. Process Description
            1. State variables
                a. Position
            2. Graphs
                a. Position versus time
        iii. Interaction Description
            1. Interaction variables
                a. Path length
                b. Distance
                c. Displacement
            2. Diagram
                a. Motion map
    b. Formulations:
        i. Dynamical Law
            1. $\vec{v} = \frac{\Delta \vec{x}}{\Delta t}$
        ii. Interaction Law
            1. $\Delta \vec{x} = x_f - x_i$
    c. Ramifications:
        i. Path length is defined as the total distance traveled along a path from starting position to ending position.
        ii. Displacement is defined as a change in the position state variable.
        iii. Speed is defined as path length per change in time.
        iv. Velocity is defined as a change in position per change in time.
        v. The slope of position versus time graph is velocity.
        vi. The area between function and time axis on velocity versus time graph is displacement.

2. Uniform Linear Acceleration Particle Model
    a. Descriptions:
        i. Object Description
            1. Object variable
                a. Acceleration
        ii. Process Description
            1. State variables
                a. Position
                b. Velocity
            2. Graphs
                a. Position versus time
                b. Velocity versus time
        iii. Interaction Description
            1. Interaction variables
                a. Path length
                b. Distance
                c. Displacement
            2. Diagram
                a. Motion map
    b. Formulations:
        i. Dynamical Laws
            1. $\vec{a} = \frac{\Delta \vec{v}}{\Delta t}$
            2. $v_x = v_{x0} + a_x t$
            3. $x = x_0 + v_{x0} t + \frac{1}{2} a_x t^2$
        ii. Interaction Law
            1. $v_x^2 = v_{x0}^2 + 2a_x(x - x_0)$
    c. Ramifications:
        i. Acceleration is defined as a change in velocity per change in time.
        ii. Slope of a velocity versus time graph is acceleration.
        iii. Area between function and time axis on acceleration versus time graph is velocity.

3. Impulsive-Force and Conservation of Momentum Model
    a. Descriptions:
        i. Object Description
            1. Object variable
                a. Momentum
        ii. Process Description
            1. State variables
                a. Velocity
                b. Mass
            2. Graphs
                a. Velocity versus time
        iii. Interaction Description
            1. Interaction variables
                a. Force
                b. Impulse
            2. Diagrams
                a. Force diagram
                b. Free-body diagram
                c. Motion map
                d. System interaction diagram
    b. Formulations:
        i. Dynamical Laws
            1. $\vec{F} = \frac{d\vec{p}}{dt}$
            2. $\vec{J} = \int \vec{F} dt = \Delta\vec{p}$
        ii. Interaction Laws
            1. $\vec{p} = m\vec{v}$
            2. $\vec{p}_{1i} + \vec{p}_{2i} + \cdots = \vec{p}_{1f} + \vec{p}_{2f} + \cdots$
    c. Ramifications:
        i. From changes in momentum, we infer forces.
        ii. From forces, we deduce changes in momentum.
        iii. Impulse is defined as the change in momentum or the integral of the force multiplied by time.
        iv. Momentum is defined as the mass multiplied by velocity.
        v. Momentum and energy are conserved in elastic collisions.
        vi. Momentum is conserved but energy is not conserved in inelastic collisions.

4. Balanced Force Model
    a. Descriptions:
        i. Object Description
            1. Object variable
                a. Force
        ii. Process Description
            1. State variable
                a. Acceleration
                b. Mass
        iii. Interaction Description
            1. Diagrams
                a. Force diagram
                b. Free-body diagram
                c. Motion map
                d. System interaction diagram
    b. Formulations:
        i. Interaction Law
            1. $\sum \vec{F} = \vec{F}_{net} = 0$
    c. Ramifications:
        i. Forces are interactions between two objects.
        ii. Forces can be classified as either contact or non-contact.
        iii. From changes in velocity, we infer forces.
        iv. From forces, we deduce changes in velocity.
        v. Objects acted upon by balanced forces will not accelerate; instead, they remain at constant velocity.
        vi. Forces are symmetric interactions (exist in pairs); paired forces are equal in magnitude but opposite in direction.

5. Unbalanced Force Model
    a. Descriptions:
        i. Object Description
            1. Object variables
                a. Force
                b. Spring constant
                c. Coefficient of friction
        ii. Process Description
            1. State variable
                a. Acceleration
                b. Mass
            2. Graph
                a. Acceleration versus time
        iii. Interaction Description
            1. Interaction variables
                a. Displacement
            2. Diagrams
                a. Force diagram
                b. Free-body diagram
                c. Motion map
                d. System interaction diagram
    b. Formulations:
        i. Interaction Laws
            1. $\vec{a} = \frac{\sum \vec{F}}{m} = \frac{\vec{F}_{net}}{m}$
            2. $\left|\vec{F}_f\right| \leq \mu \left|\vec{F}_N\right|$
            3. $\vec{F}_S = -k\Delta\vec{x}$
    c. Ramifications:
        i. Acceleration is directly proportional to net force and inversely proportional to mass.
        ii. The numerical value for coefficient of friction is determined by the surfaces.
        iii. Springs are an example of a restoring force, and each spring has a spring constant.

6. Constant Angular Velocity Particle Model
    a. Descriptions:
        i. Object Description
            1. Object variables
                a. Angular velocity
        ii. Process Description
            1. State variables
                a. Angle
                b. Mass
                c. Radius
            2. Graphs
                a. Angle versus time
        iii. Interaction Description
            1. Interaction variables
                a. Path length
                b. Angular displacement
            2. Diagram
                a. Motion map
    b. Formulations:
        i. Dynamical Law
            1. $\vec{\omega} = \frac{\Delta\vec{\theta}}{\Delta t}$
        ii. Interaction Laws
            1. $\Delta\vec{\theta} = \theta_f - \theta_i$
            2. $s = r\theta$
            3. $v = r\omega$
    c. Ramifications:
        i. Path length is defined as the total distance traveled along a path from starting position to ending position.
        ii. Angular displacement is defined as a change in the angle state variable.
        iii. Angular velocity is change in angle per change in time.
        iv. The slope of angle versus time graph is angular velocity.
        v. The area between function and time axis on angular velocity versus time graph is angular displacement.
        vi. The relationship between path length and angle is determined by the distance from the particle to the axis of rotation.
        vii. The relationship between tangential and angular velocities is determined by the distance from the particle to the axis of rotation.

7. Uniform Angular Acceleration Particle Model
    a. Descriptions:
        i. Object Description
            1. Object variable
                a. Angular acceleration
        ii. Process Description
            1. State variables
                a. Angle
                b. Angular velocity
                c. Mass
            2. Graphs
                a. Angle versus time
                b. Angular velocity versus time
        iii. Interaction Description
            1. Interaction variables
                a. Path length
                b. Angular displacement
            2. Diagram
                a. Motion map
    b. Formulations:
        i. Dynamical Laws
            1. $\vec{\alpha} = \frac{\Delta\vec{\omega}}{\Delta t}$
            2. $\omega = \omega_0 + \alpha t$
            3. $\theta = \theta_0 + \omega_0 t + \frac{1}{2}\alpha t^2$
        ii. Interaction Laws
            1. $\omega_x^2 = \omega_{x0}^2 + 2\alpha_x(\theta - \theta_0)$
            2. $a = r\alpha$
    c. Ramifications:
        i. Angular acceleration is defined as a change in angular velocity per change in time.
        ii. The slope of an angular velocity versus time graph is angular acceleration.
        iii. The area between function and time axis on angular acceleration versus time graph is angular velocity.
        iv. The relationship between tangential and angular accelerations is determined by the distance from the particle to the axis of rotation.

8. Central Net Force Model
    a. Descriptions:
        i. Object Description
            1. Object variables
                a. Force
        ii. Process Description
            1. State variables
                a. Frequency
                b. Angular velocity
                c. Velocity
                d. Centripetal acceleration
                e. Mass
                f. Radius
            2. Graphs
                a. Angular velocity versus time
                b. Angular acceleration versus time
        iii. Interaction Description
            1. Diagrams
                a. Force diagram
                b. Free-body diagram
                c. System interaction diagram
    b. Formulations:
        i. Dynamical Laws
            1. $T = \frac{2\pi}{\omega} = \frac{1}{f}$
        ii. Interaction Laws
            1. $a_c = \frac{v^2}{r} = \omega^2 r$
            2. $v = r\omega$
            3. $F_c = \frac{mv^2}{r}$
    c. Ramifications:
        i. The period of an object in circular motion is defined as the time needed to make one complete rotation.
        ii. As an object travels in a curved path, the direction of the velocity changes.
        iii. Acceleration (centripetal) from the velocity change in direction points toward the center of the circle.
        iv. Force diagrams for an object undergoing circular motion show a net force directed toward the center of the circle.

9. Energy Storage and Transfer Model
    a. Descriptions:
        i. Object Description
            1. Object variables
                a. Energy
                b. Spring constant
        ii. Process Description
            1. State variables
                a. Velocity
                b. Mass
                c. Power
            2. Graphs
                a. Velocity versus time
        iii. Interaction Description
            1. Interaction variables
                a. Work
                b. Force
                c. Displacement
            2. Diagrams
                a. Force diagram
                b. Free-body diagram
                c. Energy bar chart (LOL diagram)
    b. Formulations:
        i. Dynamical Laws
            1. $K = \frac{1}{2}mv^2$
            2. $P = \frac{dE}{dt}$
            3. $P = \vec{F} \cdot \vec{v}$
        ii. Interaction Laws
            1. $\Delta E = W = \int \vec{F} \cdot d\vec{r}$
            2. $\Delta U_g = mg\Delta h$
            3. $U_S = \frac{1}{2}k(\Delta x)^2$
    c. Ramifications:
        i. Energy is not disembodied; it is either stored in an object or by a field.
        ii. Kinetic energy is the energy stored by a moving object.
        iii. Elastic energy is stored in a deformable body.
        iv. The magnitude of potential energy depends on the strength of the field and arrangement of objects in the field.
        v. 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.
        vi. Energy can be transferred between a system and the surroundings by working, heating, or radiating.
        vii. Power is the rate of energy transfer.

10. Rigid Body Rotation Model
   a. Descriptions:
      i. Object Description
         1. Object variables
            a. Angular momentum
            b. Rotational kinetic energy
            c. Torque
      ii. Process Description
         1. State variables
            a. Angle
            b. Angular velocity
            c. Angular acceleration
            d. Center of mass
            e. Moment of inertia
            f. Radius
      iii. Interaction Description
         1. Diagrams
            a. Force diagram
            b. Free-body diagram
            c. Energy bar chart (LOL diagram)
   b. Formulations:
      i. Interaction Laws
         1. $\vec{\tau} = \vec{r} \times \vec{F}$
         2. $\vec{\alpha} = \frac{\sum \vec{\tau}}{I} = \frac{\vec{\tau}_{net}}{I}$
         3. $I = \int r^2 dm = \sum m\, r^2$
         4. $x_{cm} = \frac{\sum m_i x_i}{\sum m_i}$
         5. $\vec{L} = \vec{r} \times \vec{p} = I\vec{\omega}$
         6. $K = \frac{1}{2} I\omega^2$
   c. Ramifications:
      i. Every object has a center of mass, but this point may not be in the geometric middle of the object.
      ii. Moment of inertia of an object is related to the shape and orientation of the object.
      iii. Total kinetic energy of an object is the sum of translational kinetic energy and rotational kinetic energy.
      iv. The torque an object experiences is related to where and how forces are applied.
      v. Angular momentum of an object is related to the moment of inertia and angular velocity of the object.

11. 2-D Motion Model
   a. Descriptions:
      i. Object Description
         1. Object variable
            a. Velocity
      ii. Process Description
         1. State variables
            a. Position
            b. Acceleration
         2. Graphs
            a. Position versus time
            b. Acceleration versus time
      iii. Interaction Description
         1. Interaction variables
            a. Path length
            b. Distance
            c. Displacement
         2. Diagram
            a. Motion map
   b. Formulations:
      i. Dynamical Laws
         1. $x = x_0 + v_{x0}t + \frac{1}{2}a_x t^2$
         2. $y = y_0 + v_{y0}t + \frac{1}{2}a_g t^2$
      ii. Interaction Laws
         1. $v_x^2 = v_{x0}^2 + 2a_x(x - x_0)$
         2. $v_y^2 = v_{y0}^2 + 2a_g(y - y_0)$
   c. Ramifications:
      i. A projectile moves horizontally and vertically and traces a parabolic path in the absence of air resistance.
      ii. Horizontal and vertical motion of projectile are independent; time is the link between the two directions.

12. Harmonic Motion Model

a. Descriptions:
   i. Object Description
      1. Object variables
         a. Position
         b. Velocity
         c. Acceleration
   ii. Process Description
      1. State variables
         a. Mass
         b. Spring constant
         c. Length of pendulum
         d. Amplitude
      2. Graphs
         a. Position versus time
         b. Velocity versus time
         c. Acceleration versus time
   iii. Interaction Description
      1. Interaction variable
         a. Period
      2. Diagrams
         a. Force diagram
         b. Free-body diagram
         c. Motion map

b. Formulations:
   i. Dynamical Laws
      1. $x = A\cos(\omega t + \varphi)$
      2. $v = -\omega A\sin(\omega t + \varphi)$
      3. $a = -\omega^2 A\cos(\omega t + \varphi)$
   ii. Interaction Laws
      1. $T_S = 2\pi\sqrt{\frac{m}{k}}$
      2. $T_p = 2\pi\sqrt{\frac{l}{g}}$

c. Ramifications:
   i. A plot of position versus time for ideal mass-spring or pendulum system follows repeating function (either sine or cosine).
   ii. The period for a mass-spring system depends on mass and spring constant.
   iii. The period for a pendulum depends on length and acceleration due to gravity.

13. Gravitational Motion Model
   a. Descriptions:
      i. Object Description
         1. Object variable
            a. Force
      ii. Process Description
         1. State variables
            a. Period
            b. Radius
         2. Graph
            a. Period versus radius
      iii. Interaction Description
         1. Interaction variables
            a. Gravitational potential energy
         2. Diagrams
            a. Force diagram
            b. Free-body diagram
            c. System interaction diagram
   b. Formulations:
      i. Dynamical Law
         1. $\left(\frac{4\pi^2}{GM}\right)r^3 = T^2$
      ii. Interaction Laws
         1. $\left|\vec{F}_G\right| = \frac{Gm_1m_2}{r^2}$
         2. $U_G = -\frac{Gm_1m_2}{r}$
   c. Ramifications:
      i. The motion of an object in orbit does not depend on the object's mass.
      ii. The relationship the cube of the radius and square of the period is true for circular and elliptical orbits.

Electricity and Magnetism:

1. Electric Field and Force Model
    a. Object Description
        1. Object variable
            a. Electric charge
    ii. Interaction Description
        1. Interaction variables
            a. Electric force
            b. Electric field
            c. Radius or distance
        2. Diagrams
            a. Free-body diagram
            b. Force diagram
            c. Electric field diagram
            d. System interaction diagram
    b. Formulations:
        i. Interaction Law
            1. $\left|\vec{F}_e\right| = \frac{1}{4\pi\epsilon_0}\left|\frac{q_1 q_2}{r^2}\right|$
            2. $\vec{E} = \frac{\vec{F}_e}{q}$
            3. $\vec{E} = \frac{1}{4\pi\epsilon_0}\frac{q_1}{|\vec{r}|^2}\hat{r}$
    c. Ramifications:
        i. All matter is composed of charged particles, with varying charge mobility in different materials.
        ii. Like charges repel but opposite charges attract.
        iii. Neutral matter may be polarized, creating a localized electric field.
        iv. Electric force is dependent on charges and distance.
        v. The electric field vector points in the same direction as the electric force vector.
        vi. The permittivity of free space (ε_0) is included as a constant in the electric force and electric field equations.

2. Electric Potential Model
    a. Descriptions:
        i. Object Description
            1. Object variables
                a. Charge
                b. Radius
                c. Vacuum permittivity
        ii. Interaction Description
            1. Interaction variables
                a. Electric field
                b. Electric potential energy
                c. Electric potential
                d. Path length
            2. Diagram
                a. Equipotentials for point charges
                b. Equipotentials for continuous charge distributions
    b. Formulations:
        i. Interaction Law
            1. $E_x = -\frac{dV}{dx}$
            2. $\Delta V = -\int \vec{E} \cdot d\vec{r}$
            3. $V = \frac{1}{4\pi\varepsilon_0} \sum_i \frac{q_i}{r_i}$
            4. $U_E = qV = \frac{1}{4\pi\varepsilon_0} \frac{q_1 q_2}{r}$
    c. Ramifications:
        i. Electric potential is a property of location, not a material.
        ii. 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.
        iii. Electric potential energy is difficult to measure, so instead we typically measure electric potential.

3. Magnetic Field Model
    a. Descriptions:
        i. Object Description
            1. Object variables
                a. Charge
                b. Vacuum permeability
                c. Radius
        ii. Process Description
            1. State variable
                a. Current
            2. Graphs
                a. Charge versus time
        iii. Interaction Description
            1. Interaction variables
                a. Magnetic field
                b. Inductance
                c. Magnetic potential energy
            2. Diagram
                a. Magnetic fields of bar magnets
                b. Magnetic fields of short piece of current-carrying wire
                c. Magnetic fields of continuous current distributions
    b. Formulations:
        i. Dynamical Law
            1. $I = \frac{dQ}{dt}$
        ii. Interaction Laws
            1. $\vec{B} = \frac{\mu_0}{4\pi}\frac{q\vec{v}\times\hat{r}}{r^2}$
            2. $d\vec{B} = \frac{\mu_0}{4\pi}\frac{Id\vec{l}\times\hat{r}}{r^2}$
            3. $B_S = \mu_0 nI$
            4. $U_L = \frac{1}{2}LI^2$
    c. Ramifications:
        i. Magnetic fields originate from charge motion.
        ii. Field strength diminishes with distance from moving charge and increases with increasing charge motion.
        iii. Fields are loops and can be described with the right-hand rule.
        iv. Energy can be stored as a magnetic field in a solenoid.

4. Resistor Model
    a. Descriptions:
        i. Object Description
            1. Object variables
                a. Current
                b. Drift velocity
                c. Length
                d. Number of charge carriers per unit volume
                e. Resistivity
        ii. Interaction Description
            1. Interaction variables
                a. Electric field
                b. Resistance
            2. Diagram
                a. Electric schematic
                b. Wire diagram
    b. Formulations
        i. Interaction Laws
            1. $R = \frac{\rho l}{A}$
            2. $\vec{E} = \rho\vec{J}$
            3. $I = Nev_d A$
            4. $R_s = \sum_i R_i$
            5. $\frac{1}{R_p} = \sum_i \frac{1}{R_i}$
    c. Ramifications:
        i. Resistance is the net effect of atomic level 'obstacles' interfering with the motion of charge carriers.
        ii. Resistance is directly proportional to resistivity of the material and length, and inversely proportional to cross-sectional area.
        iii. Resistance adds when resistors are connected in series, and reduces when resistors are connected in parallel.

5. Capacitor Model
    a. Descriptions:
        i. Object Description
            1. Object variables
                a. Area
                b. Charge
                c. Dielectric constant
                d. Separation distance
                e. Vacuum permittivity
        ii. Interaction Description
            1. Interaction variables
                a. Capacitance
                b. Electric potential
                c. Electric potential energy
            2. Diagram
                a. Capacitor diagram
                b. Electric schematic
    b. Formulations
        i. Interaction Laws
            1. $C = \frac{\kappa \varepsilon_{0A}}{d}$
            2. $\Delta V = \frac{Q}{C}$
            3. $C_p = \sum_i C_i$
            4. $\frac{1}{C_s} = \sum_i \frac{1}{C_i}$
            5. $U_C = \frac{1}{2} Q \Delta V = \frac{1}{2} C (\Delta V)^2$
    c. Ramifications:
        i. Creating an uneven distribution of charge produces an electric field and electric potential difference between two locations.
        ii. Capacitance adds when capacitors are connected in parallel, and reduces when capacitors are connected in series.
        iii. Capacitance is directly proportional to the dielectric constant and surface area, and inversely proportional to plate separation distance.

6. Circuit Model
    a. Descriptions:
        i. Object Description
            1. Object variables
                a. Capacitance
                b. Electric potential
                c. Resistance
        ii. Process Description
            1. State variable
                a. Charge
                b. Current
            2. Graphs
                a. Charge versus time
                b. Current versus time
        iii. Interaction Description
            1. Interaction variables
                a. Power
            2. Diagram
                a. Electric schematic
    b. Formulations:
        i. Dynamical Laws
            1. $I = I_0 e^{-t/RC}$
            2. $Q = CV(1 - e^{-t/RC})$
            3. $Q = Q_0 e^{-t/RC}$
        ii. Interaction Laws
            1. $I = \frac{\Delta V}{R}$
            2. $P = I\Delta V$
    c. Ramifications:
        i. A conducting path allows constrained charge motion between the points as an uneven charge distribution is maintained.
        ii. 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.
        iii. The voltage gains and drops around a closed loop of a circuit is equal to zero.
        iv. The rate at which charge accumulates on a capacitor or current flows in a RC circuit depends on the resistance and capacitance.

7. Magnetic Force Model
    a. Descriptions:
        i. Object Description
            1. Object variables
                a. Area
                b. Charge
                c. Current
                d. Current per unit length
                e. Magnetic field
                f. Number of turns per unit length
                g. Velocity
        ii. Interaction Description
            1. Interaction variables
                a. Magnetic dipole moment
                b. Magnetic force
                c. Torque
            2. Diagram
                a. Free-body diagram
                b. Force diagram
                c. Magnetic field of a solenoid
                d. System interaction diagram
    b. Formulations:
        i. Interaction Laws
            1. $\vec{F}_M = q\vec{v} \times \vec{B}$
            2. $\vec{F}_M = \int I\, d\vec{l} \times \vec{B}$
            3. $\vec{\tau} = \vec{\mu} \times \vec{B}$
            4. $|\vec{\mu}| = nIA$
    c. Ramifications:
        i. Force is exerted on a charge moving in a magnetic field.
        ii. Directions of force, charge/current, and magnetic field can be found with the right-hand rule.
        iii. A current-carrying coil or magnetic dipole experiences torque in a magnetic field and twists to align with the applied magnetic field.

8. Electromagnetism Model
    a. Descriptions:
        i. Object Description
            1. Object variables
                a. Area
                b. Charge
                c. Current
                d. Electric field
                e. Inductance
                f. Length
                g. Magnetic field
                h. Time
                i. Vacuum permeability
                j. Vacuum permittivity
        ii. Process Description
            1. State variables
                a. Electromotive force (emf)
            2. Graphs
                a. Magnetic flux versus time
                b. Current versus time
        iii. Interaction Description
            1. Interaction variables
                a. Electric flux
                b. Electromagnetic force
                c. Electromotive force (emf)
                d. Magnetic flux
            2. Diagram
                a. Amperian loop
                b. Free-body diagram
                c. Force diagram
                d. Gaussian surface
    b. Formulations:
        i. Dynamical Laws
            1. $\varepsilon = \oint \vec{E} \cdot d\vec{l} = -\frac{d\Phi_B}{dt}$
            2. $\varepsilon = -L\frac{dI}{dt}$
        ii. Interaction Laws
            1. $\varepsilon = \oint \vec{E} \cdot d\vec{l}$
            2. $\Phi_E = \oint \vec{E} \cdot d\vec{A} = \frac{Q}{\varepsilon_0}$
            3. $\oint \vec{B} \cdot d\vec{l} = \mu_0 I$
            4. $\Phi_B = \int \vec{B} \cdot d\vec{A}$
            5. $\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$
    c. Ramifications:
        i. Electric flux is the quantitative measure of the amount and direction of electric field over an entire surface.

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

APPENDIX C – CONNECTION BETWEEN MODELS AND LEARNING OBJECTIVES

This appendix shows the relationship between each model and the learning objectives (College Board, 2014) for models in AP Physics C: Mechanics and Electricity and Magnetism. Standards beginning with “M” are Mechanics; those beginning with “EM” are Electricity and Magnetism.

Table C.1

Learning objectives for each model in Mechanics and Electricity and Magnetism

Model Name	Learning Objectives
Mechanics	
Constant Linear 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
Uniform Linear 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
Impulsive-Force and Conservation of Momentum Model	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
Balanced Force Model	M.B.1, M.B.2.b.2, M.B.3.a, M.B.3.b, M.B.3.c
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
Constant Angular Velocity Particle Model	M.E.3.a
Uniform Angular Acceleration Particle Model	M.E.3.a
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

Model Name	Learning Objectives
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
Rigid Body Rotation 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.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
2-D Motion Model	M.A.2.b, M.A.2.c.1, M.A.2.c.2
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
Gravitational Motion Model	M.F.4.a, M.F.4.b, M.F.4.c, 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
Electricity and Magnetism	
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.b.1, EM.A.4.b.2.a, EM.A.4.b.2.b, EM.A.4.b.3, EM.B.1.a.1, EM.B.1.a.2, EM.B.1.a.3
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, EM.A.4.a.3, EM.A.4.b.4, EM.B.1.b
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

Model Name	Learning Objectives
Resistor Model	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
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, 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
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
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
Electromagnetism Model	EM.A.3.a.1, EM.A.3.a.2, EM.A.3.a3, EM.A.3.b.1, EM.A.3.b.2, EM.A.3.b.3, EM.B.1.c.1, EM.B.1.c.2, EM.B.1.c.3, EM.B.1.c.4, EM.D.4.b.1, EM.D.4.b.2, EM.D.4.c, 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

APPENDIX D – SEQUENCE OF MODELS IN AP PHYSICS C FOR 2017-2018

This appendix describes the sequence of models in AP Physics C for 2017-2018. The order of models is changing because I want to incorporate rotation into the course sooner; during 2016-2017, students had the most difficulty with the Rigid Body Rotation Model. This model—and the Central Net Force Model—have been broken into the following models: Angular Momentum Model, Balanced Torque Model, and Unbalanced Torque Model. I hopes this change will allow students to have a deeper conceptual understanding, leading to better development of the rotational models.

Mechanics:

1. Constant Linear Velocity Model
2. Constant Angular Velocity Model
3. Uniform Linear Acceleration Model
4. Uniform Rotational Acceleration Model
5. 2-D Motion Model
6. Linear Momentum Model
7. Angular Momentum Model
8. Balanced Force Model
9. Unbalanced Force Model
10. Central Net Force
11. Balanced Torque Model
12. Unbalanced Torque Model
13. Energy, Work, and Power Model
14. Oscillations Model
15. Gravitation 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 E – DISAGGREGATION OF DATA ACCORDING TO PRIOR PHYSICS COURSES

In addition to the raw data, I opted to disaggregate data on the basis of previous physics course. For the Mechanics section, 3 students had completed AP Physics 1, 10 students had completed Honors Physics, and 7 students had no prior physics experience. Tables E.1 through E.3 provide the disaggregated information for Mechanics.

Though the number of students with each prior physics course is low, interesting patterns emerged from the data. Students who completed AP Physics 1 had the highest mean score on the pretest and posttest of both the FCI and MBT. In addition, these students had the highest Raw and Normalized Gains on the MBT; however, students who completed AP Physics 1 had the lowest Raw and Normalized Gains on the FCI. Instead, the students who completed Honors Physics and students with no prior physics course had higher Raw and Normalized Gains on the FCI. On the 2015 AP Physics C: Mechanics Practice Exam, students who completed AP Physics 1 unsurprisingly had higher mean scores on the multiple-choice and free response of the pretest. However, all groups had approximately the same mean score on the multiple-choice portion of the posttest; students who completed Honors Physics and students with no prior physics course had higher Raw and Normalized Gains. On the free response section, students who completed AP Physics 1 had the highest posttest mean score—leading to the highest Raw and Normalized Gains. Combining the multiple-choice and free response sections leads to an overall AP score; on the pretest, students who completed AP Physics 1 had the highest mean. However, all groups performed roughly the same on the posttest. Students from all groups performed roughly the same on the 2017 AP Physics C: Mechanics Exam; students who completed AP Physics 1 had the highest mean whereas the other two groups had more variance in their scores.

Table E.1

Student data on the FCI and MBT, disaggregated by prior physics course

Prior Physics Level	FCI Pretest (%)	FCI Posttest (%)	Raw Gain (%)	Normalized Gain	MBT Pretest (%)	MBT Posttest (%)	Raw Gain (%)	Normalized Gain
AP 1	70	80	10	.33	46	62	16	.30
AP 1	83	97	14	.82	65	85	20	.57
AP 1	83	83	0	.00	50	81	31	.62
Mean	79	87	8	.39	54	76	22	.50
Median	83	83	10	.33	50	81	20	.57
Honors	43	63	20	.35	37	54	17	.27
Honors	47	77	30	.57	27	54	27	.37
Honors	60	77	17	.43	46	35	-11	-.20
Honors	63	93	30	.81	42	73	31	.53
Honors	70	90	20	.67	54	77	23	.50
Honors	70	87	17	.57	62	65	3	.08
Honors	73	90	17	.63	46	62	16	.30
Honors	73	77	4	.15	50	62	12	.24
Honors	77	83	6	.26	46	58	12	.22
Honors	83	90	7	.41	54	73	19	.41
Mean	66	83	17	.48	46	61	15	.27
Median	70	85	17	.50	46	62	17	.28
None	30	40	10	.14	35	46	11	.17
None	43	50	7	.12	46	54	8	.15
None	43	83	40	.70	37	65	28	.44
None	50	63	13	.26	42	50	8	.14
None	57	77	20	.47	42	54	12	.21
None	57	90	33	.77	50	73	23	.46
None	63	97	34	.92	42	85	43	.74
Mean	49	71	22	.48	42	61	19	.33
Median	50	77	20	.47	42	54	12	.21

Table E.2

Student data for each section of the 2015 AP Physics C: Mechanics Practice Exam, disaggregated by prior physics course

Prior Physics Level	Pretest MC (%)	Posttest MC (%)	Raw Gain (%)	Normalized Gain	Pretest FR (%)	Posttest FR (%)	Raw Gain (%)	Normalized Gain
AP 1	31	40	9	.13	11	24	13	.15
AP 1	57	71	14	.33	33	73	40	.60
AP 1	51	43	-8	-.16	27	60	33	.45
Mean	46	51	5	.10	24	53	29	.40
Median	51	43	9	.13	27	60	33	.45
Honors	34	37	3	.05	18	40	22	.27
Honors	37	49	12	.19	18	40	22	.27
Honors	26	49	23	.31	16	36	20	.23
Honors	43	69	26	.46	27	60	33	.45
Honors	43	63	20	.35	18	40	22	.27
Honors	46	69	23	.43	33	73	40	.60
Honors	69	71	2	.06	33	73	40	.60
Honors	31	51	20	.29	11	24	13	.15
Honors	31	57	26	.38	11	24	13	.15
Honors	46	63	17	.31	27	60	33	.45
Mean	41	58	17	.28	21	47	26	.34
Median	40	60	20	.31	18	40	22	.27
None	20	51	31	.39	20	44	24	.31
None	29	34	5	.07	7	16	9	.09
None	23	54	31	.40	16	36	20	.23
None	23	37	14	.18	18	40	22	.27
None	40	66	26	.43	31	69	38	.55
None	23	66	43	.56	22	49	27	.34
None	40	63	23	.38	16	36	20	.23
Mean	28	53	25	.35	19	41	23	.29
Median	23	54	26	.39	18	40	22	.27

Table E.3

Student data of the AP scores on the 2015 AP Physics C: Mechanics Practice Exam and 2017 AP Physics C: Mechanics Exam, disaggregated by prior physics course

Prior Physics Level	2015 Practice Exam AP Score - Pretest	2015 Practice Exam AP Score - Posttest	2017 Exam AP Score
AP 1	1	3	4
AP 1	3	4	4
AP 1	2	3	4
Mean	2.00	3.33	4.00
Median	2.00	3.00	4.00
Honors	3	5	5
Honors	2	3	4
Honors	2	4	4
Honors	1	3	3
Honors	1	3	2
Honors	1	2	2
Honors	1	3	3
Honors	1	4	4
Honors	3	4	4
Honors	1	2	2
Mean	1.60	3.30	3.30
Median	1.00	3.00	3.50
None	1	1	2
None	2	4	4
None	1	4	4
None	1	3	1
None	1	2	3
None	1	4	5
None	1	3	4
Mean	1.14	3.00	3.29
Median	1.00	3.00	4.00

For the Electricity and Magnetism section, 3 students had completed AP Physics 1, 7 students had completed Honors Physics, and 6 students had no prior physics experience. Tables E.4 through E.6 provide the disaggregated information for Electricity and Magnetism.

Although students who completed AP Physics 1 had some experience with Electricity and Magnetism principles, students in this group did not show any difference on the BEMA and EMCA pretest or posttest means than the other two groups. Students with no prior physics course performed slightly worse than the other two groups on the BEMA and EMCA posttests, leading to the lowest Raw and Normalized Gain on the BEMA. On the 2015 AP Physics C: Electricity and Magnetism Practice Exam, students performed at approximately the same level for the multiple-choice and free response sections on both the pretest and posttest. Because the scores were similar, the Raw and Normalized Gains are similar for the multiple-choice and free response sections on both the pretest and posttest. Students struggled greatly with the free response section on the pretest; this section had students supply answers, which proved difficult. Students improved on the free response section of the posttest, though the mean scores were still in the 20% to 25% range. Combining the multiple-choice and free response sections leads to an overall AP score; on the pretest, all groups of students performed at approximately the same level whereas students who completed AP Physics 1 had a slightly higher posttest mean than the other two groups. On the 2017 AP Physics C: Electricity and Magnetism Exam, students who completed AP Physics 1 had the highest mean; students in the other two groups had much lower means.

Table E.4

Student data on the BEMA and EMCA, disaggregated by prior physics course

Prior Physics Level	BEMA Pretest (%)	BEMA Posttest (%)	Raw Gain (%)	Normalized Gain	EMCA Pretest (%)	EMCA Posttest (%)	Raw Gain (%)	Normalized Gain
AP 1	3	27	24	.25	50	67	17	.34
AP 1	23	50	27	.35	53	73	20	.43
AP 1	30	70	40	.57	50	83	33	.66
Mean	19	49	30	.39	51	74	23	.48
Median	23	50	27	.35	50	73	20	.43
Honors	17	40	23	.28	50	67	17	.34
Honors	23	33	10	.13	23	40	17	.22
Honors	27	40	13	.18				
Honors	27	73	46	.63	40	83	43	.72
Honors	30	37	7	.10	27	77	50	.68
Honors	33	47	14	.21	50	80	30	.60
Honors	37	60	23	.37	50	80	30	.60
Mean	26	48	21	.29	43	72	29	.51
Median	27	47	23	.28	50	76	27	.54
None	20	63	43	.54	37	73	36	.57
None	23	37	14	.18	37	63	26	.41
None	23	47	24	.31	37	60	23	.37
None	23	40	17	.22	43	83	40	.70
None	33	50	17	.25	50	70	20	.40
None	33	17	-16	-.24	23	60	37	.48
Mean	26	42	17	.21	38	68	30	.49
Median	23	44	17	.24	37	67	31	.45

Table E.5

Student data for each section of the 2015 AP Physics C: Electricity and Magnetism Practice Exam, disaggregated by prior physics course

Prior Physics Level	Pretest MC (%)	Posttest MC (%)	Raw Gain (%)	Normalized Gain	Pretest FR (%)	Posttest FR (%)	Raw Gain (%)	Normalized Gain
AP 1	26	49	23	.31	0	16	16	.16
AP 1	29	51	22	.31	7	22	15	.16
AP 1	31	40	9	.13	11	40	29	.33
Mean	29	47	18	.25	6	26	20	.22
Median	29	49	22	.31	7	22	16	.16
Honors	31	34	3	.04	7	22	15	.16
Honors	17	31	14	.17	9	20	11	.12
Honors	31	40	9	.13	4	29	25	.26
Honors	34	49	15	.23	11	36	25	.28
Honors	29	40	11	.15	7	18	11	.12
Honors	26	43	17	.23	11	24	13	.15
Honors	26	54	28	.38	11	38	27	.30
Mean	28	43	15	.21	8	26	18	.20
Median	29	43	15	.23	7	24	16	.16
None	40	46	6	.10	9	33	24	.26
None	23	34	11	.14	2	9	7	.07
None	29	37	8	.11	16	16	0	.00
None	29	40	11	.15	13	22	9	.10
None	26	49	23	.31	7	20	13	.14
None	37	49	12	.19	2	16	14	.14
Mean	31	43	12	.17	8	19	11	.12
Median	29	43	11	.15	8	18	11	.12

Table E.6

Student data of the AP scores on the 2015 AP Physics C: Electricity and Magnetism Practice Exam and 2017 AP Physics C: Electricity and Magnetism Exam, disaggregated by prior physics course

Prior Physics Level	2015 Practice Exam AP Score - Pretest	2015 Practice Exam AP Score - Posttest	2017 Exam AP Score
AP 1	1	3	3
AP 1	1	4	5
AP 1	1	3	3
Mean	1.00	3.33	3.67
Median	1.00	3.00	3.00
Honors	1	4	3
Honors	1	3	3
Honors	1	2	1
Honors	1	2	1
Honors	1	3	2
Honors	2	4	4
Honors	1	2	2
Mean	1.11	2.93	2.52
Median	1.00	3.00	3.00
None	1	1	2
None	2	2	2
None	1	2	2
None	1	3	2
None	2	4	4
None	1	3	3
Mean	1.33	2.50	2.50
Median	1.00	2.50	2.00

APPENDIX F – 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 [redacted email address]. 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 G – PERMISSION TO USE INFORMATION

I received permission to use Figures 2.1, 2.2, 2.3, 2.4, 2.5, 2.6, and 2.7 and Table 2.2 from Dr. David Hestenes via email communication on October 10, 2015.

I 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. I agreed not to use any information related to specific questions or reproduce specific questions, and the analysis will be performed with aggregate student scores.