Investigating the impact of a LEGO-based, engineering-oriented curriculum compared to an inquiry-based curriculum on fifth graders' content learning of simple machines

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INVESTIGATING THE IMPACT OF A LEGO™-BASED, ENGINEERING-ORIENTED CURRICULUM COMPARED TO AN INQUIRY-BASED CURRICULUM ON FIFTH GRADERS’ CONTENT LEARNING OF SIMPLE MACHINES

Dissertation
by

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INVESTIGATING THE IMPACT OF A LEGO-BASED, ENGINEERING-ORIENTED CURRICULUM COMPARED TO AN INQUIRY-BASED CURRICULUM ON FIFTH GRADERS’ CONTENT LEARNING OF SIMPLE MACHINES

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This mixed method study examined the impact of a LEGO-based, engineering-oriented curriculum compared to an inquiry-based curriculum on fifth graders’ content learning of simple machines. This study takes a social constructivist theoretical stance that science learning involves learning scientific concepts and their relations to each other. From this perspective, students are active participants, and they construct their conceptual understanding through the guidance of their teacher.

With the goal of better understanding the use of engineering education materials in classrooms the National Academy of Engineering and National Research Council in the book “Engineering in K-12 Education” conducted an in-depth review of the potential benefits of including engineering in K–12 schools as (a) improved learning and achievement in science and mathematics, (b) increased awareness of engineering and the work of engineers, (c) understanding of and the ability to engage in engineering design, (d) interest in pursuing engineering as a career, and (e) increased technological literacy
(Katehi, Pearson, & Feder, 2009). However, they also noted a lack of reliable data and rigorous research to support these assertions.

Data sources included identical written tests and interviews, classroom observations and videos, teacher interviews, and classroom artifacts. To investigate the impact of the design-based simple machines curriculum compared to the scientific inquiry-based simple machines curriculum on student learning outcomes, I compared the control and the experimental groups’ scores on the tests and interviews by using ANCOVA. To analyze and characterize the classroom observation videotapes, I used Jordan and Henderson’s (1995) method and divide them into episodes.

My analyses revealed that the design-based Design a People Mover: Simple Machines unit was, if not better, as successful as the inquiry-based FOSS Levers and Pulleys unit in terms of students’ content learning. I also found that students in the engineering group outperformed students in the control group in regards to their ability to answer open-ended questions when interviewed. Implications for students’ science content learning and teachers’ professional development are discussed.
DEDICATION

To my parents Huriye and Kemal who have always been there to support me.

And to my wife, Muserref, who has supported me with her love and pushed me forward on this journey.
First, I'd like to thank my thesis advisor and CO-PI of the TESLED project, Mike Barnett, for guiding me throughout my graduate career. I will forever be grateful for his continuous support, advice and guidance. He thought me being multitasking and focused at the same time. He provided me opportunities to work with colleagues from other institutions in the area and to engage with science education community across the country. Throughout my graduate career, he was an exemplary advisor, and I will try to be like him once I have advisees in the future. I also would like to thank the other two committee members, Kate McNeill, who has improved my work with intellectual support and provided me a successful science education researcher’s point of view, and Alec Peck, who has provided thoughtful comments and critiques.

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CHAPTER 1: INTRODUCTION

Over the past twenty years, we have witnessed a dramatic increase in students’ use of and access to technology. Advancements in science and technology have shaped individual lives as well as the lives of societies. Scientific and technological discoveries in the twentieth century include: radio, television, satellites, synthetics, penicillin, the internet, nuclear energy, and genetic engineering, all of which have dramatically affected life on earth. The progress in the first decade of the twenty-first century confirmed that science and technology will still be powerful elements influencing humanity in the twenty-first century. Who would have imagined ten years ago that it would be possible to have a touch-screen computer in your pocket that can be used to surf the web, read your e-mail, play music, read books, and watch movies? Who would have predicted that 36.1% of American children ages 10 -11 own a cell phone (Mediamark Research & Intelligence, 2010)? What underlies this rapid increase in the access to technology is engineering design. Engineering has always been recognized as an important part of education and of a nation’s social and economic well-being. But over the past decade, engineering has dramatically increased in importance as many countries have placed research and development of new technologies at the top of their national agendas, and as leaders have recognized that it is through technological and/or scientific advancement that their societies will continue to thrive into the twenty-first century.

In the United States, there is an increasing trend for engineering education to be integrated in grades K through 12; however, it is still unsatisfactory. The National
Academy of Engineering (NAE) and the National Research Council (NRC) reports that the number of students enrolled in K-12 classrooms was about 56 million in 2008, but since 1990, less than 6 million students had any formal engineering education (Katehi, Pearson, & Feder, 2009). This means that less than 10 percent of students between 1990 and 2008 have had some type of formal engineering education.

On the other hand, countless aspects of our lives are managed by technological products that were made possible by science and engineering. Only a few in the “technological elite” (that is, mostly professional scientists and engineers) show competence in science and feel comfortable using technology. As human lives are increasingly influenced by technological issues such as energy sources, global warming, internet security, agricultural engineering, health technology, and genetic engineering, the need for the general public to be familiar with technology and to be empowered to make wise decisions about technological issues is greater than ever. The basic pre-requisite for this empowerment process is increased understanding of science and technology.

In order to increase the understanding of science and technology, the foundations for science and technology education should be laid as early as the elementary grades. A number of national educational policy institutes including the National Research Council (NRC), the National Academies (NA), the National Science Education Standards (NSES), and the American Association for the Advancement of Science (AAAS) emphasized this position in their recent national policy statements. For example, the National Academies (National Academy of Sciences, National Academy of Engineering, and Institute of Medicine) in “Rising Above the Gathering Storm” (NA, 2006), calls for
increased exposure to engineering and technology and improved instruction in science at all levels of education, while the NSES encourages students to familiarize themselves with engineering design by engaging in design activities (National Research Council, 1996). The NSES argues that “children’s abilities in technological problem solving can be developed by firsthand experience in tackling tasks with a technological purpose” (NRC, 1996 p. 135). Similarly, under Project 2061, the American Association for the Advancement of Science (AAAS) argues that,

Perhaps the best way to become familiar with the nature of engineering and design is to do some. By participating in such activities, students should learn how to analyze situations and gather relevant information, define problems, generate and evaluate creative ideas, develop their ideas into tangible solutions, and assess and improve their solutions. To become good problem solvers, students need to develop drawing and modeling skills, along with the ability to record their analyses, suggestions, and results in clear language (AAAS, 1993, p. 48).

Not only do individuals need science and technology knowledge for surviving in twenty-first century society, but also the society needs scientifically and technologically literate citizens to survive and to improve its merit among other societies. Continuous growth, power and economic development are inevitably dependent on technological and scientific advancement (NA, 2006). To keep its technology and science going forward, the United States needs a technically and scientifically literate society and a workforce that is trained in both engineering and scientific processes. The increase in oriented daily life
practices indicates the importance of science and technology education starting with the elementary grades (NRC, 2004).

In addition to policymakers’ claims, standardized test results of United States students show the need for improving elementary science education. For example, in the 2005 National Assessment for Educational Progress (NAEP) test in science for Grade 4 across the U.S., 32% scored “Below Basic,” and 39% scored “Basic,” leaving just 29% who scored at or above the “Proficient” level (Grigg, Lauko, & Brockway, 2006). At the state level, the results from the 2008 and the 2009 Massachusetts Comprehensive Assessment System (MCAS) test for fifth grade Science and Technology/Engineering reveals that only half of the students in 2008 and only 49% of the students in 2009 scored at or above the proficient level (Massachusetts Department of Elementary and Secondary Education, 2009).

National policy reports and standardized test results suggest that there is a call for improvement in the teaching of elementary school science. On top of this challenge, other sources suggest not only improvements in science education, but also integration of engineering education is needed in elementary classrooms. In a nationwide survey commissioned by the American Society for Engineering Education (ASEE) on K-12 teachers, 90.3% of teachers agreed that “understanding more about engineering can help them become a better teacher”, and 84% agreed that “their students would be interested in learning engineering” (Douglas, Iverson & Kalyandurg, 2004). Despite this strong demand for engineering education in K-12 schools, students show a lack of engineering awareness. A recent study reported in one Massachusetts district that less than 15% of
504 elementary students, correctly identified “creating ways to clean water” as something that engineers do, while over 70 % incorrectly chose “driving machines” as a special engineering task (Cunningham, Lachapelle, & Lindgren-Streicher, 2005).

Recognition of this widespread lack of engineering awareness and technological literacy has led to a growing effort by educators and policymakers to include engineering or technological design in K–12 classrooms (Davis & Gibbin, 2002; Douglas et al., 2004; ITEA, 2000; Kolodner, 2002; Pearson & Young, 2002). In an increasingly technological world, it is even more important that students attain basic scientific and technological literacy. This is particularly important in communities where access to and success in science and technology has historically been limited. In the national and international assessments of science and mathematics there are significant differences between the performance of Hispanic and African American students and that of their White suburban peers (Berliner, 2001, 2006). NAE and NRC emphasize the lack of diversity in higher education in general and in the engineering workforce in particular (Katehi, Pearson, & Feder, 2009). For them the problem has two faces. First, minority and female students in K-12 classrooms are underrepresented in the population of students who receive formal engineering education. Second, most of the curricular materials for engineering education do not seem to be designed for attracting students from diverse ethnicities and cultures. NAE and NRC recommend that the demographic trends in the United States require that K-12 engineering curricula should be designed to attract underrepresented subpopulations to engineering education (Katehi, Pearson, & Feder, 2009).
Another challenge the nation faces today is that students do not enjoy science classes and report that they find them uninteresting and irrelevant (e.g. Briggs, 1976; Williams, Stanisstreet, Spall, Boyes, & Dickson, 2003; and Woolnough, 1994). Students’ interest in science is especially low in underrepresented minorities (Committee on Science Engineering and Public Policy, 2007). Any attempt to reform science education in a nation that is heavily dependent on its science and technology production must not ignore students’ low interest in science and engineering. It is important to find ways to make science education fun, especially during the early years of students’ exposure to science. Cunningham (2007) proposes that exposing them to engineering as early as in elementary grades may help students, especially minorities and females, to develop positive relations with engineering and encourage them to consider engineering as a career.

In her work on the Engineering is Elementary curriculum developed by the Boston Museum of Science, Cunningham (2007) describes several other reasons for introducing engineering to elementary school children. First, elementary school children are extremely interested in building and taking things apart to understand how they work. Furthermore, engineering activities integrate well with other disciplines such as science and mathematics, promote students’ problem solving skills, can help children to develop three-dimensional thinking skills, and help students gain engineering and technological literacy skills.
About This Study

In this study, LEGO™ engineering materials, which are technological as well as mechanical, are introduced as a new instructional tool. This tool is familiar to most students since many of them have played with them (or something similar) at some point in their lives. Using LEGO™ materials is a very powerful way of adding fun and motivating students in science classrooms (Cejka, Rogers, & Portsmore, 2006; Rogers & Portsmore, 2004). It not only motivates students to learn science, but also motivates teachers by helping them to increase their students’ achievement (Noble, 2001). I believe, that all of the challenges that our elementary educators face can be addressed by introducing LEGO™ materials as instructional tools and by integrating engineering-design activities into science classes. Since LEGO™ materials perfectly match with engineering-design activities, Lego-based, design-oriented activities have a great potential to improve science learning while teaching technology and increasing students’ motivation in urban schools.

Elementary teachers in the United States face multiple challenges: too many elementary students show a poor understanding of science content; stakeholders are calling for the addition of new content to introduce engineering; and students do not enjoy science classes. How can these challenges be solved? With this proposed research and development work, I argue that engineering need not be a stand-alone, add-on unit. Rather, engineering provides an authentic context for teaching science content. By using engineering design challenges as an overarching framework for science instruction, two broader goals can be achieved simultaneously: increased competence and interest in
science, and heightened awareness of the crucial role of engineering in our society. Moreover, time pressure can be alleviated. Before these outcomes can be achieved, however, researchers need to engage in systematic study of the effectiveness and best practices of using engineering design challenges to generate science learning in elementary science education.

This dissertation study investigates how LEGO™ engineering-design curriculum materials, in comparison with inquiry-based curriculum materials, may improve students’ understanding of science content and help them establish their conceptual framework about simple machines. These materials were developed with support from the National Science Foundation’s Research and Evaluation in Engineering and Science Education program (Grant # 0633952) in collaboration with the Center for Engineering Education and Outreach at Tufts University. Specifically the areas of investigation in this study include:

a) What do students learn about the science of simple machines in a LEGO-engineering design unit, in contrast to a scientific inquiry-based unit?

b) How do the characteristics of these curricula support students’ ability to learn the science of simple machines and help them develop accurate conceptions?

In this study, I use the Design a People Mover: Simple Machines unit (see Appendix A for an example lesson of the unit) as the experimental curriculum and FOSS’s Levers and Pulleys unit as the control curriculum. Simple machines were chosen as the content because gaining a conceptual understanding of simple machines is relevant to real life situations. Science and Technology Concepts (STC) and Full Option Science Systems
(FOSS) are two popular curricula used in many school systems to teach simple machines. However, I have noticed that a number of concepts (e.g. simple machines, complex machines, work, force, and conservation of energy) involved in simple machines are difficult for students to understand. Furthermore, there are only a small number of studies that investigate students’ or teachers’ understanding of simple machines in the science education literature.

**Implications and Impact of this work**

The National Academy of Engineering (NAE) and National Research Council (NRC) document the potential benefits of including engineering education in K–12 schools as (a) improved learning and achievement in science and mathematics, (b) increased awareness of engineering and the work of engineers, (c) understanding of and the ability to engage in engineering design, (d) interest in pursuing engineering as a career, and (e) increased technological literacy (Katehi, Pearson, & Feder, 2009, p. 49-50). However, NAE and NRC also report the lack of reliable data to support these assertions. They recommend that long-term research explore the impact of engineering education on students’ learning of STEM subjects and technological literacy, student engagement and retention, and career aspirations (Katehi, Pearson, & Feder, 2009). Yet another criticism of engineering education is that it has focused a lot on the design process and not so much on the science content. Most research has looked at students’ perceptions of engineers and their ability to go through the design process, but not at how it supports students’ understanding of scientific content.
This work is significant because it suggests how an engineering-design curriculum can be used to help students learn science content and improve their technological and scientific literacy. A growing recognition has emerged that engineering-design should be integrated into science education to improve students’ science content learning, develop their design skills and prepare them for scientifically and technologically oriented daily life and the even more challenging and competitive world of professional life (Kolodner, 2002, 2006). This study will contribute to this field of study by demonstrating how an engineering-design curriculum supports students’ content learning and their technological and scientific literacy skills. This study will explain how science teachers’ use of LEGO™-based, engineering-design curriculum materials in urban classrooms impacts students’ outcomes as well as how these curriculum materials can be best utilized in elementary science classrooms. This study will also contribute to the research literature by exploring how Lego-based science studies, grounded in engineering-design, might help students master the scientific concepts involved in simple machines.
CHAPTER 2. REVIEW OF THE LITERATURE

In this chapter, I briefly discuss the need for re-envisioning what elementary science looks like in elementary classrooms. Then, given that there is considerable debate within the science education and engineering education communities regarding the relationship between scientific inquiry and engineering design I discuss the epistemological similarities and differences of both domains. Then I discuss the framework upon which the LEGO™ based engineering curriculum was developed including Sternberg’s triachic principles and learning by engineering design principles. Following this, I review the research that has been conducted on design-oriented curriculum materials and their implementation and impact on student outcomes. I close this chapter with a review of projects that have specifically leveraged LEGO™ materials as an instructional tool and review the research on student conceptual understanding of simple machines.

The Need for a New Approach to Elementary Science Education

National policy reports call for improvement in elementary science, an increased exposure to engineering and technology starting with the elementary grades, and expansions in taking science to school (National Research Council, 1996); standardized test results emphasize the need for improvement in students’ science achievements at both the state level (Massachusetts Department of Elementary and Secondary Education, 2009) and the national level (Grigg & Lauko, 2006); the science education literature (e.g. Briggs, 1976; Williams, Stanisstreet, Spall, Boyes, & Dickson, 2003; and Woolnough,
1994) confirms that students do not enjoy science classes because they find them uninteresting and irrelevant.

To address the multiple challenges in the United States of improving students’ achievement in science, such as increasing their motivation and interest in science learning and improving their technological literacy (Pearson & Young, 2002), educators have suggested that technological (engineering) design activities be used as a context for science instruction (Fortus, Dershimer, Krajcik, Marx, & Mamlok-Naaman, 2004; Kolodner, 2006).

**Epistemological Similarities of Science and Technology (Inquiry and Design)**

Science and technology are epistemologically related to each other. During the course of history they have gone hand in hand. In the most general case, science is seen as a process through which humanity explores the universe and makes sense of it, while technology is seen as the application field of science, in which humans use and apply their understanding of the universe in order to master it. AAAS defines science as follows:

Over the course of human history, people have developed many interconnected and validated ideas about the physical, biological, psychological, and social worlds. Those ideas have enabled successive generations to achieve an increasingly comprehensive and reliable understanding of the human species and its environment. The means used to develop these ideas are particular ways of observing, thinking,
experimenting, and validating. These ways represent a fundamental aspect of the nature of science and reflect how science tends to differ from other modes of knowing. (AAAS, 1989, p.1)

Correspondingly, technology is described as “a complex social enterprise that includes not only research, design, and crafts but also finance, manufacturing, management, labor, marketing, and maintenance” (AAAS, 1989, p. 25).

AAAS’s description of science as “a mode of knowing” leads them to a corresponding definition for technology: modes of doing in the attempt to “change the world to suit us better (AAAS, 1989, p. 25).” Moreover, AAAS sees science, mathematics, and technology as three aspects of the scientific endeavor. Science, mathematics and technology are complementary to each other. They reinforce each other and they are powerful and successful together.

The content of the scientific endeavor itself is not only the subject and the application field, but also the very essence that holds science, mathematics and technology together. As scientific and technological issues such as clean energy sources, global warming, internet security, genetic engineering, and stem-cell research become increasingly important, there is a huge need for the general public to be empowered to make informed decisions about science and technology. This empowerment requires increased understanding of science and technology. This inspiration is conceptualized as gaining scientific literacy in national standards and benchmarks for science education. In this sense, “scientific literacy” is used as a general term denoting both technological and mathematical literacy. In the national science standards, scientific literacy is targeted as a
main objective in the following statement: “This nation has established as a goal that all students should achieve scientific literacy.” (NRC, 1996, p. IX). Since scientific literacy is such an important national goal, the current state of elementary science education is unacceptable, and it needs to be improved immediately and significantly.

**LEGO™-based, Design-oriented Elementary Science Curriculum**

Deepening science learning, increasing student and teacher motivation, and implementing the integration of engineering education in elementary levels can be accomplished concurrently by using LEGO™-based, design-oriented curricular modules in elementary science classrooms. Engaging students in design-based learning opportunities has been found to be effective in improving science education in many ways. Unfortunately, in elementary school settings, design-oriented tasks are often not implemented for various reasons. These reasons include lack of design-based curricula for elementary school students and teachers’ low self-efficacy in teaching with design-oriented tasks (National Research Council, 2004).

In this study, LEGO™ materials, which are technological as well as mechanical, are introduced as a new instructional tool. This tool is familiar to most students since many of them have been playing with LEGO™ materials since they were very young. The LEGO™-based, engineering-design model suggests that inquiry and design could support each other to accomplish both science and technology learning: design could especially support inquiry and science learning as well as engineering and technology learning.
Sternberg’s Triarchic Intelligence Principles in the Curricular Module. This study is unique in its integration of design-oriented instruction, LEGO™ engineering tools, and triarchic teaching and assessment methods (Grigorenko, Jarvin, & Sternberg, 2002) to help elementary students learn science and technology content, as well as inquiry and design processes, by engaging students in the practices of real scientists and engineers. Triarchic teaching and assessment methods refer to analytical, creative, and practical skills of the learner and define intelligence based on these three facets of learning. The theoretical framework for the curriculum intervention is based on the notion that engineering design is a natural pathway for “triarchically based” instruction and assessment, which has been shown to improve student achievement compared with conventional instruction (Grigorenko, et al., 2002; Sternberg, Grigorenko, & Jarvin, 2001).

The main difference between triarchically based instruction and the traditional instructional approaches is that it emphasizes analytical, creative, and practical thinking and learning skills in addition to traditional memory skills. In several studies of the effectiveness of triarchic instruction for primary, middle, and high school students, Sternberg and colleagues found that students exposed to triarchic instruction performed better on a variety of types of assessments in several different subject areas, including science (see Grigorenko, et al., 2002 for a review). Based on these comprehensive results, I accept triarchic intelligence theory as a useful framework for designing effective curricula, and I propose that all domains of intelligence—memory/analytical, creative, and practical—should be emphasized in classroom teaching. Within science education, I
argue that engineering design activities provide the context for the elementary science
teacher to tap into all of the different cognitive abilities involved in the triarchic
intelligence theory.

Sternberg (1985, 1986) argued that successful intelligence is achieved through a
balance of analytical, creative, and practical abilities. Thus, instruction and assessment
should address three types of knowledge: practically-based, analytically-based, and
creatively-based rather than addressing only the traditional memory-based knowledge. In
fact, Sternberg incorporated memory based knowledge into the analytic facet of
knowledge. To illustrate this theoretical framework, Table 1 provides a summary of
Sternberg’s suggestions for triarchically based classroom instruction/assessment
(Sternberg, 1985, 1986, 1997). In this table, actions and skills that students need to
perform for achieving memory, analytical, practical and creative facets of knowledge are
given separately.

Engineering-design challenges enable each of the four types of teaching within
the discipline of science. For example, the design-based learning task, “Evaluate the
validity of the simple machine that you made to lift the object” addresses memory and
analytic abilities and skills; “Using the materials provided, invent a complex machine that
can move a LEGO™-man six inches up and eighteen inches across the table” addresses
creative abilities and skills; and “Employ a simple machine in the design of a device
which can move the LEGO™-weight across the table” addresses practical abilities and
skills.
Table 1

The summary of Sternberg’s successful intelligence (Sternberg, Jarvin, & Grigorenko, 2009).

<table>
<thead>
<tr>
<th>MEMORY ACTIONS AND SKILLS</th>
<th>PRACTICAL ACTIONS AND SKILLS</th>
</tr>
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<tbody>
<tr>
<td>Recall</td>
<td>Name</td>
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<tr>
<td>Retell</td>
<td>Say</td>
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<td>Recite</td>
<td>Describe</td>
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<td>List</td>
<td>Identify</td>
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<td>Locate</td>
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<table>
<thead>
<tr>
<th>ANALYTICAL ACTIONS AND SKILLS</th>
<th>CREATIVE ACTIONS AND SKILLS</th>
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<tr>
<td>Analyze</td>
<td>Compare</td>
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<td>Contrast</td>
<td>Evaluate</td>
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<tr>
<td>Explain</td>
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<td>Organize</td>
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<td>Classify</td>
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Learning by Design-Oriented Activities. This study is one part of a larger project called Transforming Elementary Science Learning through LEGO™ Engineering Design (TESLED), a National Science Foundation (NSF) funded project. With this project, in collaboration with Boston-area elementary schools, the Center for Engineering Educational Outreach (CEEO) at Tufts University, The Center for the Psychology of Abilities, Competencies, and Expertise (PACE Center), Department of Education at Tufts
University, and the Lynch School of Education at Boston College seek to develop, implement, and evaluate innovative curriculum models that transform elementary science learning through compelling engineering design challenges. So far, four design-based elementary science curricular units have been developed and implemented: (a) Design a Musical Instrument: The Science of Sound, (b) Design a Model House: The Properties of Materials, (c) Design an Animal Model: Animal Studies, and (d) Design a People Mover: Simple Machines.

In this study, I focus on the Design a People Mover: Simple Machines unit as an instrument. In this LEGO™-based, engineering-oriented, simple machines curricular module, engineering design is embedded in the curriculum as an essential theme. It, however, does not consist only of engineering design activities. In the simple machines module, inquiry themes as well as design themes are included. This design-oriented module is designed to engage students in engineering-design processes with the end goal of solving real life problems while engaging students with basic scientific content. Nunes, Schiliemann and Carraher (1993) reported that people perform better in solving problems in their real lives or in situated circumstances; however, they perform poorly when they face those problems in test-like situations, For example, people perform four arithmetical operations better when solving everyday life problems than when solving math-test problems.

We identified three previous approaches to design-based science instruction at the elementary and middle school level: Learning by Design™ (Kolodner, 2006); design-based modeling (Penner, Giles, Lehrer, & Schauble, 1998); and engineering for children
(Roth, 1996). We believe that concentrating on these approaches will provide us with valuable insights about engineering-design as a context for science learning because these studies are representatives of the field and their theoretical principals, curricula and findings are publicly available. Along with numerous commonalities across these studies, they all define engineering design as an activity that involves the construction of a physical product that solves a human problem. Integrating these three approaches, we added the following learning objectives in order to integrate engineering process into the unit.

a) Define engineering design as the process of creating solutions to human problems through creativity and the application of math and science knowledge.

b) List and explain the following steps of the engineering design process:
   i. Identifying a problem
   ii. Researching possible solutions
   iii. Picking the best solution
   iv. Building a prototype
   v. Testing the prototype
   vi. Repeating any steps needed to improve the design.

By the end of the unit, we expect students to understand engineers’ work, engineering design, as the process of creating solutions to human problems. We also expect students to understand that this process involves application of math and science knowledge, design principles and creativity. Engineering design principles include: (i) identifying a problem, which denotes identifying the problem and investigating the relevant constraints; (ii) researching possible solutions refers to making hypotheses and conducting investigations; (iii) picking the best solution indicates evaluating, making
tradeoffs, and making decisions; (iv) building a prototype refers to modeling, generating alternatives, and using creativity; (v) testing the prototype denotes experimentation and evaluation; (vi) repeating any steps needed to improve the design includes evaluation, iteration, and optimization.

The basic blueprint of the unit is based upon the Learning by Design™ (LBD) model developed by Kolodner and colleagues at Georgia Technical University (Hmelo, Holton, & Kolodner, 2000; Kolodner, Camp, Crismond, Fasse, Gray, Holbrook, Puntambekar, Ryan, 2003; Kolodner, Gray, & Fasse, 2003). The model was developed to help middle school students (grades 6 to 8; ages 12 to 14) comprehend science content, transfer this knowledge to new situations, and participate competently in the practice of scientists.

For this study, the Learning by Design™ (LBD) model is transformed for elementary science teaching and enriched by integrating LEGO™ materials as an instructional tool and Sternberg’s triarchic intelligence principles to create the instructional and assessment methods of the curricular module. LBD model is based on five principles, which emphasize the daily practices of skilled practitioners such as scientists, engineers, and industrial designers. These principles include (a) foregrounding of skills and practices, (b) practicing, (c) establishing need, (d) making recognition of the need to use procedures automatic, and (e) establishing and enforcing expectations (Kolodner, 2002). The design challenges generate a motivation for learning the science content, and engaging in design challenges provides natural settings and procedures for practicing inquiry and design skills. The need for creating a working model of design
ideas helps students to identify and rectify their imperfect and poor conceptions, while natural iterations in the design processes allow them to apply and test new conceptions. Also, the collaborative practices of team work offer students the opportunity to improve in communicating ideas and results (Kolodner, 2002).

Engineering design activities offer students not only an environment for learning science content, but also opportunities for application of the knowledge that they gain in different situations and for engaging in the practices of scientists and engineers (Kolodner, 2002). Kolodner explains the characteristics of LBD as follows:

In *Learning By Design* (LBD), the design challenge provides a reason for learning the science content, and engaging in the challenge provides a natural and meaningful venue for using both science and design skills. The need to make one's design ideas work provides opportunities and reasons for students to identify incomplete and poor conceptions of science content and to debug those conceptions; the iterative nature of design provides opportunities to apply and test new conceptions; and the collaborative nature of design provides opportunities for team work and the need to communicate ideas and results well (Kolodner, 2002, p. 3).

In LBD activities, students engage in design challenges. To provide solutions for the design challenges, students need to comprehend related science content. Design activities give students the opportunity to go through a trial and error process. In this process, students have a chance to improve their conceptual understanding either by reinforcing their novice ideas or by confronting their misunderstandings and changing them with
appropriate conceptions in the iterative testing practice. Figure 1 represents Kolodner, Gray, and Fasse’s (2003) model of the cycles of activities involved in learning from design activities.


Kolodner et al. (2003) defined two parallel cycles of activities in the design-based learning. The sequence of the design/redesign cycle includes playing with materials and devices to understand the challenge, engaging in a problem-based learning to define what needs to be investigated, planning a design, constructing, testing, and analyzing the design. The sequence of the investigate and explore cycle includes clarifying the question, generating a hypothesis about it, designing the investigation, conducting and analyzing it, and finally presenting and sharing it in a poster session. Because LBD is an iterative process, these cycles or any activity from the cycles can be repeated as needed.
As students engage in these activities in an iterative process, they have an opportunity to perform many skills and practices.

Kolodner (2002) defined the science and technology skills and practices in LBD. The science skills and practices include (a) understanding a problem and what might need to be investigated, (b) generating questions that can be investigated, (c) investigation with a purpose (i.e. experimentation, modeling, learning from cases, managing variables, accurate observation and measuring, seeing patterns, etc.), (d) informed decision making, reporting on and justifying conclusions, (e) iteration towards understanding, (f) explaining scientifically, (g) investigation planning, (h) communication of ideas, results, interpretations, implications, justifications, explanations, principles, (i) teamwork, collaboration across teams, giving credit.

The corresponding technology skills and practices include (a) identifying criteria, constraints, problem specifications, (b) “messing about” with and understanding materials, (c) investigation for the purpose of application-designing and running models, reading and learning from case studies, etc., (d) informed decision making, reporting on and justifying design decisions, (e) iteration towards a good enough solution, (f) explaining failures and refining solutions, (g) prioritizing criteria, trading them off against each other, and optimizing, (h) communication of ideas, design decisions, justifications, explanations, design rules of thumb, (i) teamwork, collaboration across teams, giving credit. By foregrounding these skills and practices, LBD incorporates both scientific inquiry and technological design skills.
Most of these skills align with our engineering-design principles. Our principles integrate science and technology skills and practices. For example, *identifying a problem* and *researching possible solutions* incorporate some technological skills and practices such as identifying constraints, generating questions, and investigating purposefully; but in addition these principles also involve science skills and practices such as understanding the problem, making hypotheses and conducting investigations to solve the problem. Furthermore, *picking the best solution*, *building a prototype*, *testing the prototype*, and *repeating any steps needed to improve the design* incorporate some science practices and skills such as experimentation, modeling, justifying conclusions, iteration towards understanding, and making scientific explanations, but also involve technological skills and practices such as generating alternatives, prototyping, evaluating and justifying failures, refining solutions in an iterative process, making tradeoffs, and optimization.

**Design-based Instruction in the Literature**

In the science education literature, many studies show that design activities help students gain the abilities that are needed to understand science content and to perform inquiry. Much of the literature documents the benefits of design-based instruction over the traditional instructional approach in which rote memorization of facts is the basis.

Traditional science curricula and instruction materials are not only based on rote memorization of facts but also an inanimate scientific process (Penner, Lehrer, & Schauble, 1998). For example, most science textbooks define the scientific method by using a modularized form (proposing a hypothesis, conducting an experiment, evaluating
results, and drawing conclusions), so that students understand natural phenomena and
generate new knowledge (Penner, Lehrer, & Schauble, 1998). Moreover, in traditional
science instruction, teachers assign students problems that can be solved by following the
instructions rather than challenging them to solve real life problems. These types of
exercises can lead students to form the flawed perception that scientists follow step-by-
step textbook instructions to reach universally accepted truths through known givens
(facts and data) (Jungck, Peterson, & Calley, 1992). In contrast to the traditional
approach, there is a growing base of research that describes science and the scientific
process as a design process in which the understanding of natural phenomena emerges
and co-evolves through scientific discourse, open-ended and real life problem solving,
inquiry, and the design and construction of shareable artifacts (Pappert, 1991; Peterson,
Jungck, Sharpe, & Finzer, 1987; Roth, 1996). These perceptions are consistent with the
view of science as a design activity. This view is appropriate, since in that scientific
investigations typically begin with a set of goals and hypotheses concerning what the
investigator is interested in understanding (Peterson et al., 1987). These goals influence
the design/scientific process and evolve as the process proceeds, because they are often
ill-defined and uncertain by nature (Jungck et al., 1992; Perkins, 1986).

The designing-to-learn perspective opens many exciting opportunities for learning
science content. For example, when students are engaged in collaborative design
activities in which they need to define the problem themselves, they engage in open-
ended problem solving and eventually resolve the problem with the construction of a
shareable artifact (Papert, 1991; Roth, 1996). Additionally, engaging in design activities
in the science classroom provides opportunities for students to engage in problem-solving activities that are authentic to the science content, and the design process require students to analyze the content under study and develop the skills needed to represent it to others in a way that helps them to understand the content (Harel & Papert, 1992). In addition, as students engage in design practices, they develop an understanding of how knowledge is structured and intertwined with purpose, function, and causal relations (Perkins, 1986). During the design practices, students are engaged directly in the process of constructing knowledge rather than receiving it from someone else, and this puts them in a discourse that more realistically characterizes communities of practice in science and engineering (Roth, 1996).

The literature includes various studies focusing on design activities in different levels of science and engineering teaching. In a recent study, Atman, Kilgore and McKenna (2008) explored engineering designers’ use of language at the college level. They explored freshmen students’ conceptions of two topics -human energy needs and global climate change- and compared the conceptions of engineering and non-engineering students. They found that taking a course in engineering design or studying engineering for four years help students develop engineering design language, which is commonly used by the engineering community, their own programs, and their higher learning institutes. Authors suggest that engineering language shapes students’ engineering design knowledge; however, students have problems putting their engineering knowledge into practice. With this statement, Atman et al. (2008) confirms the need for early exposure to engineering education including engineering-design
practices. College students who had practiced engineering design activities in their elementary and/or secondary education became familiar not only with engineering design language, but also with engineering design practices. Since engineering design is involved with real contexts (Atman & Nair, 1996; Kilgore et al., 2007) and involves people working together to solve real life problems that address societal as well as personal needs (Atman, Kilgore, & McKenna, 2008), this means that, whether or not they study engineering, students who were exposed to engineering design in the early years of their education become technologically literate individuals.

In another recent study focusing on high school level teaching with design activities, Barnett (2005) investigated urban high school students who learned science through designing remote operated vehicles. Barnett implemented the design-based Remote Operated Vehicles (ROV) curriculum in an urban school in Massachusetts as an extra-curricular activity set. His study documents that in a high-poverty urban high school environment, the design-based ROV curriculum was successful in (a) increasing students’ attendance, (b) helping students engage by developing ownership of the project, (c) teaching physics content to students and helping them recognize connections to other coursework, and (d) helping teachers shift their roles from discipline and content keeper to coach and facilitator.

Barnett (2005) reports that design activities are more successful when they are modularized in urban high schools because, as a modularized activity, a student can enter the activity at anytime and start working with other students. The modularized structure of the ROV curriculum helps students who have irregular attendance engage in the
activities smoothly and without feeling any alienation. The modularized structure of science curricula would be helpful for special education students and English as Second Language (ESL) learners as well. Since special education and ESL students often have to skip a part of their science learning time for their special or ESL classes, they have difficulty engaging in and keeping up with the science instruction. Modularized science curricula would help them engage in the activities more quickly. In addition to this, science teachers could keep better track of what modules of the curriculum those students missed. Then they could help those students accordingly to complete the missing parts of the curriculum.

The research literature on elementary school science teaching suggests that engaging students in engineering design learning opportunities is an effective way of helping students understand how to manipulate and model data (Lehrer & Romberg, 1996), which, in turn, helps students develop domain specific knowledge. In their study, Lehrer and Romberg assigned fifth grade students in groups to design hypermedia documents about Colonial America. The context of the hypermedia documents was a comparison of classmates’ lifestyle with the colonists’ lifestyles. They formed six different design teams including four students in each to develop the hypermedia documents. In each group, students had different roles. The most central role was of the data analysts, who developed data collection tools, collected and coded data, and summarized the data to the other members of the team to answer any questions relevant to the purpose of the design. In each team, more than one member assumed this role.
Other tasks that students were assigned to do in their teams include use and interpretation of data to generate new questions and drawing deductive conclusions.

Kolodner (2002) compared middle school students’ science learning with Learning-by-Design (LBD) activities and with traditional methods by implementing two LBD activities, the parachute challenge and the balloon-car challenge, in the experimental group. She found that students who participated in LBD activities learned as well or better than the students who learned the content with traditional methods. Along with content knowledge, LBD students learn many skills that scientists and designers often use in their professions. In a similar study, Kolodner, Gray, and Fasse (2003) documented that LBD students engaged in collaboration, communication, informed decision making, and design of investigations more skillfully than the students in control groups.

In another middle school study, Cantrell, Pekcan, Itani, and Velasquez-Bryant (2006) investigated the effects of engineering modules on student learning in science classrooms. With the Teacher Integrating Engineering into Science (TIES) program, authors paired university faculty from the College of Education and College of Engineering at the University of Nevada, Reno with middle school science teachers. Collaboratively, the faculty and the science teachers created three engineering units that include lesson plans, web-based simulation activities, engineering design activities, materials and standard assessments. Each unit focuses on a science topic that is consistent with district and state science content standards. The three units focused on balloons, bumper cars, and bridges, respectively. Different student population groups’ mean scores
in the unit assessments were compared with their mean scores in the 2004 Nevada eighth
grade science Criterion Reference Test (CRT). Engineering design units had reduced
performance gaps in science among different student populations. For example,
compared with the CRT test scores, in the TIES test, achievement gaps for low SES
students, special education students, Hispanic students, and Black students were reduced.

It was observed during the instruction that students were highly engaged in the
engineering design activities, and teachers reported higher levels of student excitement.
Cantrell et al. (2006) believed that engineering design experiences offer engaging
opportunities for students that help them acquire conceptual understanding of science
content and develop higher order thinking skills such as analysis and synthesis. Cantrell
et al. (2006) describe the advantages of early exposure to engineering design challenges
as follows:

Exposing all children to engineering design problems at lower grade levels
would offer a powerful and successful approach for learning science
concepts. Using this approach, a wide, variety of students could become
engaged with rigorous content as they grapple with design problems that
require mastery of science and mathematics concepts. (p.308)

Early exposure to engineering education would increase students’ scientific and
mathematical literacy as well as their technological literacy. Additionally, early exposure
to engineering may have potentially increase female students’ interest in engineering.

Similarly, many other researchers have identified middle school as a crucial
period in terms of either encouraging or discouraging students’ participation and interest
in mathematics, science, and engineering as a profession (Brophy, Klein, Portsmore, & Rogers, 2008; English, Daves, Hudson, & Byers, 2009; Tafoya, Nguyen, Skokan, & Moskal, 2005). Thus, students’ exposure to mathematics, science and engineering at or before middle school is critical. This is particularly important for engineering because, unlike mathematics and science, engineering is not part of most school curricula.

Lehrer & Romberg (1996) document that engaging in a design activity that includes data construction and analysis offers students an opportunity to engage in the important enterprise of research. In their study, students were specifically involved in mathematical modeling. These kinds of experiences help students improve not only their content knowledge but also their inquiry and design skills. In the light of their results, Lehrer & Romberg conclude that “Design provides a context for meaningful inquiry; data structures, statistics, and inference can be used as tools to develop knowledge that, in turn, has a place within the larger framework of a design” (p.71).

**Use of LEGO™ Materials as an Instructional Tool**

One unique aspect of this study is the way which it integrates in engineering design into elementary science education. Integrating a new discipline into elementary science education requires developing and supporting new tools for the classroom. Rogers and Portsmore (2004) explain how use of LEGO™ materials as an instructional tool can help introduce engineering into elementary schools. A common misconception about educational technology is that technology means computers, so students should learn how to use a computer. However, the computer is just one of the technological tools that help human beings solve problems. The criteria for testing the quality of a learning
toolset include its flexibility to use and age appropriateness. LEGO™ materials appear as excellent tools for elementary school teaching. Rogers and Portsmore (2004) outline a variety of design challenges that they used to teach different subjects such as math, science, reading, writing, and engineering. The authors also documented that students are able to learn important science and mathematics concepts with LEGO™ materials as early as the first grade. Moreover, teachers are surprised to see how engineering activities with LEGO™ materials keep students’ attention for a long time and how students complain when the time is over.

LEGO™ materials can appropriately be used as an instructional tool in various levels of education. Ringwood, Monaghan and Maloco (2005) taught engineering design to undergraduate engineering students through Lego® Mindstorms™. In a freshmen engineering course, students were assigned to accomplish engineering tasks such as collecting drink-cans on a table. To accomplish the task, first, students needed to design a robot that can run and collect drink-cans on the table, and second, they needed to program the motors and the sensors to bring tracking, navigating, and picking up skills to the robot by using the Mindstorms software. After the instruction, the majority of the engineering freshmen agreed that they became more interested in engineering as a result of being taught through Lego® Mindstorms™. Ringwood et al. (2005) agreed that a comprehensive engineering technology like Lego® Mindstorms™ can inspire creativity, demonstrate a practical and enjoyable engineering experience, and offer an opportunity to experience the social aspects of real engineering work. They found Lego® Mindstorms™ “[sufficiently flexible] to implement an enormous range of designs for a variety of
problem domains [and] highly visual and intuitive, since it is based on a learning toy which many students will already have some familiarity with, while the ability to incorporate ‘intelligence’ through software is both attractive and characteristic of most modern engineering applications” (p. 103).

The study by Ringwood et al. (2005) is a typical example of the use of Lego® Mindstorms™. They argue that Lego® Mindstorms™ “engenders the creative spirit at an early stage” (p. 103) for freshmen engineering students. I would like to take this argument even further by documenting that using Lego® Mindstorms™ in science classrooms as an instructional tool also engenders the creative spirits of fifth grade students. In fact, Lego® Mindstorms™ is age-appropriate (8+) for fifth graders.

**Challenges to Success in Teaching by LEGO™-based, Engineering-Design Module**

Unfortunately, the ill-structured nature of design activities has prevented it from being implemented in under-resourced urban classrooms, and for the most part learning-by-design activities have been relegated to resource-rich demonstration sites (Roth, 1996; Roth, Tobin, & Ritchie, 2001), in out-of-school settings (Davis, Hawley, McMullan & Spilka, 1997), or as a part of funded university-sponsored initiatives (Hmelo, Holton, & Kolodner, 2000; Sadler, Coyle, & Schwartz, 2000). To date, little research has been done to examine how design-oriented learning activities play out in under-resourced urban inner-city elementary science classrooms.

Kolodner (2002) identified three major challenges to success in teaching by engineering design: (1) teacher preparation, (2) assessment of skills and student learning, and (3) time management. In this study, I am not focusing on these challenges; however,
it is important to be aware of these challenges because they inform us in designing viable and quality curricula and instruction to teach science. For example, many teachers in elementary science classrooms give up on teaching science, or teach science in a superficial way, because their confidence level is teaching science is pretty low (Cochran and Jones, 1998). They have low confidence levels because they either do not have a strong content knowledge in science, [especially in physical sciences] (Anderson and Mitchener, 1994) or they do not have strong technology skills. Thus, a successful implementation of an engineering-design module is highly dependent on teachers’ preparedness to teach by engineering-design. Teacher preparation for teaching with engineering-design activities should include time management skills, technology skills, and teaching and assessing with engineering-design skills. To prepare teachers for using LEGO™ engineering design units in their classrooms, we conducted a teachers’ workshop during the summer before they started teaching. I also stayed connected with teachers during the implementation of the units to answer their questions and discuss any issues they encountered.

In addition, Barnett (2005) urged teachers to be aware that during the design activities, some students may focus on aesthetics rather than functionality in their design; therefore, teachers should encourage students to learn the content by creating functional and useable designs rather than to entertain themselves by creating aesthetically pleasing designs. Similarly, Rogers and Postmore (2004) urge teachers to be continuously supportive and facilitating during teaching with engineering design, or else, it will often revert to “LEGO™ playtime”.

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In summary, to date a number of studies have explored the impact of engaging design activities in science teaching and learning at different levels. In those studies, some of the points highlighted are: engineering design is involved with real contexts (Atman & Indira, 1996; Kilgore et al., 2007); it connects with social processes (Bucciarelli, 1996); it involves people working together to solve real life problems that address societal as well as personal needs (Atman, Kilgore, & McKenna, 2008); it offers an excellent opportunity for students to learn the iterative nature of science and the meaning of testing alternatives in problem-solving (Bers and Postmore, 2005); it generates motivation for learning science content (Kolodner, 2002; Barnett, 2005), even for students who think that they are “not good at”, or “not interested” in science and mathematics (Bers and Urrea, 2000); engineering design engagees both genders, a variety of learning styles and multiple intelligences (Rogers and Postmore, 2004); and in engineering process, there is no one right way of representing or solving problems: it involves multiple representations and multiple solutions (Atman et al., 2007; Atman, Kilgore, & McKenna, 2008).

Along with those features, design-based instruction offers a wonderful context to integrate different subjects such as math, science, humanities and social sciences (Benenson, 2001). By incorporating hands-on constructing activities, engineering-design promotes three-dimensional thinking and visualization, improves students’ technological literacy (Roth, 1998; Sadler, Coyle, & Schwartz, 2001), and provides an essential platform for project-based learning by allowing students to illustrate theoretical scientific principles in everyday contexts (Resnick, Berg, & Eisenberg, 2000).
Potential benefits of using engineering design in elementary science education include improved achievement and understanding of science content, improved inquiry and design skills, increased technological literacy, increased awareness of engineering and interest in engineering as a career; however, as the National Academy of Engineering (NAE) and the National Research Council (NRC) report, there are only limited reliable data available to support those arguments (Katehi, Pearson, & Feder, 2009). Especially, little research has been done to investigate the impacts of using engineering design on elementary students’ science content learning. While many studies have examined how middle school, high school and college students engage in science through design activities (e.g., Atman et al., 2008; Barnett, 2005; Cantrell et al., 2006; Kolodner, 2002), only a few studies (e.g. Roth, 1996; Penner et al., 1998) have investigated the use of engineering design programs in elementary schools. Finally, there is an increasing trend that sees science and the scientific process from a design perspective. With these highlights, engineering design appears to be a promising way to solve the multiple challenges that elementary science education faces today.

**Conceptual Understanding in Science Education**

There is a wealth of literature about conceptual understanding in science education. Some studies illustrate the conceptual difficulties that students and teachers have, while others provide research-based methods to target and refine misconceptions. In his Students’ and Teachers’ Conceptions and Science Education database¹ (2009), Duit

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¹ [http://www.ipn.uni-kiel.de/aktuell/stcse/download_stcse.html](http://www.ipn.uni-kiel.de/aktuell/stcse/download_stcse.html)
lists around 8,400 studies that have explored teachers’ and students’ understanding of scientific concepts. The large number of entries in the bibliography and the research literature itself suggests that, from youth to old age, human beings naturally develop their own theories and models to explain the natural world around them based on interpretations of their own experiences and observations. Learning-sciences try to conceive this process to find ways to help learners to obtain scientifically correct conceptualizations of the natural world. However, when I searched through the bibliography for the terms “simple machine”, “pulley”, “inclined plane”, “ramp”, “wheel and axle”, “wedge”, or “screw”, I did not come across any studies, and I only came across one for each of the terms “gear” and “levers”. Therefore, in the following sections I will briefly discuss the different perspectives that researchers have used to study how students’ conceptions change and develop over time. The reason for this is that much of the work in conceptual changes has examined the underlying physical science concepts upon which the science of simple machines is built.

Cognitive Perspectives on Conceptual Science Learning. The idea of seeing science learning as conceptual change has its roots in the work of Piaget. Piaget (1952) used the terms: assimilation and accommodation to describe two phases of learning. Assimilation involves interpreting sensory information and bringing it into agreement with the existing knowledge structures, while accommodation involves giving a meaning to the new information and adapting it (Scott, Asoko, and Leach, 2007). Piaget’s work mainly stresses the development of logical capabilities as the individual matures.
However, Ausubel (1968) argues that individuals’ existing conceptual knowledge is more important than any other factor that affects individuals’ conceptual understanding.

During the second half of the twentieth century conceptual change has become a widely used term among educational researchers. Many researchers have defined conceptual change from different perspectives. For example, some researchers refer to exchange of a single concept as conceptual change, while others consider exchange of the whole web of concepts as conceptual change, and some others consider a change in the relationships between concepts as conceptual change.

Posner, Strike, Hewson, and Gertzog (1982) explained conceptual change by drawing an analogy to Kuhn’s notion of a paradigm shift. In this view, students are analogous to scientists, and conceptual change for students is equivalent to paradigm shift for scientists. By following Toulmin (1972), Strike and Posner (1992) used the term ‘conceptual ecology’ to label conceptual context. ‘Conceptual ecology’ perfectly identifies a web of interrelated concepts instead of a single concept. Thus, constructing a conceptual understanding has nothing to do with understanding a single concept, but rather involves understanding and relating a web of concepts and their functions. Changing a student’s conception involves changing his or her conceptual ecology rather than simply exchanging one concept for another; it is therefore, hard and time consuming (Posner et al., 1982; Strike & Posner, 1992).

Restructuring is another term that is used for explaining conceptual change. Carey (1988, 1999) argues that knowledge is restructured in the course of acquisition, and restructuring has two senses that are weak and strong. For Carey, restructuring is at least
of the sort that has been described for adults undergoing a novice-expert shift in a scientific domain. She exemplifies the weak restructuring with gaining expertise in chess and the strong restructuring with the transition from Aristotelian mechanics to Galilean mechanics. Carey (1988, 1999) expanded the definition of conceptual change to a scale where novice-expert shift is at one end and theory change in the course of historical cases is at the other end. Carey (1999) argues that conceptual change does not occur suddenly; rather it takes a fair amount of time for a child, an adult or an individual scientist to restructure their knowledge. Similarly, it can be argued that conceptual change for a child during the developmental process, for a student, for an adult, or for an individual scientist, are all different kinds of processes.

Unlike Carey, Ioannides and Vosniadou (2001) found that the term “force” expressed similar meanings both in the history of science and in children’s explanations. They identified two meanings of “force”: “the initial meanings of force” (before systematic instruction) and “the synthetic meanings of force” (during and after instruction). Like scientists in the history of science, children see force as an internal property of inanimate objects and as an agent that moves or stops objects. Moreover, as acquisition of an explanatory framework caused revolutions in the history of science, it motivates students to spontaneously change their understanding of force from the internal force meaning to the acquired force meaning. Although students’ conceptual change has many similarities with scientists’ theory change, unlike scientists, students are not meta-conceptually aware of the conceptual change, nor are they thoroughly testing hypotheses in the learning process.
For Ioannides and Vosniadou, the process of conceptual change involves: (i) adopting a new representation to explain a phenomenon, (ii) refining the same framework, and (iii) creating a new framework. Ioannides and Vosniadou (2001) also advocate that conceptual change could take place before systematic instruction. They explain that theory building and a change in the initial theory possibly happen before the school age. Thus, not only instruction but also life experiences initiate conceptual change. This latter point has significant implications for engineering education as much of the material that has been developed within the field of engineering education support students in building or designing objects to help them solve a problem in their everyday lives.

In the science education research literature there are two leading views about the initial conceptual structures of phenomena. There is the naïve theories view (Vosniadou, 1989; Vosniadou and Brewer, 1992), in which students are considered as novice theory builders, and the phenomenological primitives (p-prims) view (diSessa, 1988), which maintains that students’ knowledge is in pieces called p-prims.

Vosniadou and Brewer (1992) see children as active theory builders and define conceptual reformation as theory change. Vosniadou and Brewer (1992) built their theory on Piaget’s (1929) view that children are active theory builders and their initial mental models of phenomena are based on their everyday experience with the world. They investigated elementary school children’s initial mental models of the earth in the first, third and fifth grades and their change over time. Vosniadou and Brewer found that students hold initial mental models of the earth such as the rectangle earth, the disk earth,
the dual earth, the hollow sphere, and the flattened sphere. They also found that the
rectangle earth and the disk models existed even before children were exposed to the
culturally accepted sphere earth model. These mental models result from children’s
interpretations of their everyday experiences and their presuppositions about them. The
ability to interpret everyday experiences and to derive presuppositions from them makes
children naïve theory builders. Then, in the course of schooling, children modify these
mental models and acquire the culturally accepted model; however, this progress occurs
gradually and transitional synthetic models emerge during the process. The way in which
Vosniadou and Brewer (1992) view children as naïve theory builders suggests that
children’s presuppositions form their knowledge. To make changes in students’
conceptual understanding, one should make sure that students reinterpret their
presuppositions within a different cognitive framework.

On the other hand, diSessa and his colleagues claim that students’ initial
structures are unconnected pieces that remain unchanged but their applications vary in
(1988, 1993) argues that the human brain stores knowledge in pieces that reflect very
basic and simple relations. He called these pieces *phenomelogical primitives (p-prims)*
(diSessa, 1993). In support of the knowledge in pieces theory, Southerland, Abrams,
Cummins, and Anzelmo (2001) clearly defined the notion of a p-prim. They argue that p-
prims “are understood to be atomistic knowledge structures that are automatically and
unconsciously activated by the learner in response to a particular situation” (p. 329).
Similarly, Ueno (1993) defined p-prims as “… fundamental pieces of knowledge that are
understood by the learner to need no explanation, as they operate as implicit presuppositions of how the physical world works” (p. 329-330).

Smith, diSessa, and Roschelle (1993/94) argue that conceptual change is knowledge refinement and reorganization of pieces of knowledge. They see students’ preconceptions as useful for instruction to reorganize and refine their knowledge. DiSessa and Sherin (1998) called the cognitive strategies to select and organize the knowledge pieces coordination classes. Students who gather knowledge by rote memorization often lack understanding of how small pieces of knowledge connect and contribute to each other and form a meaningful conceptual picture (diSessa, 1988; Ebenezer, 1992). Since they lack coordination classes, they could not store this information in their long-term memory (Novak, 1993).

Similarly, Minstrell (1982) investigated how students store knowledge. He assumes that students’ knowledge is in pieces that he called “facets”, and that they use these pieces in a learning situation to construct their understanding of phenomena. He argues that knowledge change “… will involve the addition of facets based on concrete experience. As more and more concrete knowledge is gained through experience, the facet may become grouped with additional qualifier facets that help define appropriate contexts of application” (p. 120). Minstrell’s facets represent a synthesis of coordination classes and p-prims. Minstrell names each meaningful product resulting from a coordination of p-prims a facet. When the child learns different coordination classes, then new facets are formed. It is this coordination that is particularly relevant to engineering education. Since much of engineering focuses
on engaging students in building slowly their knowledge of a particular design or domain through the continuous testing and revision of their emerging ideas. Thus, one could argue that design-based engineering projects are ideal contexts for supporting the development of students’ conceptual understandings.

**Conceptual Science Learning Through Engineering-Design.** Engineering design activities with LEGO™ materials as an artifact will serve as an appropriate context for teaching and learning scientific concepts. In LEGO™-based engineering design activities, students will be able to experience concrete, real-life situations that will help them to construct appropriate scientific concepts. Also, the *Design a People Mover: Simple Machines* unit will serve as a wonderful framework in which students refine their preconceptions about simple machines and construct appropriate conceptions. Moreover, engineering-design activities with LEGO™ materials require connecting pieces of knowledge to each other with meaningful relations and organizing them into a coherent working framework to solve a given problem.

There is a growing research community that believes students need to have experience with phenomena in three dimensions because students are struggling to transform 2D views into 3D objects (i.e. pictures in books); however, a 3D view is required for complete conceptual understanding of many concepts (Gotwals, 1995; Windschitl, Winn, & Headley, 2001). For example, a 3D LEGO™ model of a lever allows students to have direct experiences with the key concepts of levers such as leverage, fulcrum, load arm, leverage arm, etc. By using a LEGO™ lever, students have many opportunities to examine their understanding from multiple perspectives. Students
can change the load, the effort, or the load and the leverage arms by changing the place of the fulcrum. Engaging in these explorations, students can test their existing conceptual framework from different viewpoints.

To make conceptual change possible, the first step is for students to become dissatisfied with their existing conceptual understanding. Then a meaningful change can occur (Posner, Strike, Hewson, & Gertzog, 1982; Strike & Posner, 1992). Students engaging in engineering design activities and building models with LEGO™ materials can easily test their existing understanding with their model and restructure their conceptual framework based upon their experience and interactions with their three-dimensional LEGO™ models (Penner et al., 1998). Engaging students in activities in which they can have direct experiences with the key concepts of the study would facilitate conceptual change (Demastes, Good, & Peebles, 1995; diSessa & Minstrell, 1998).

Most of the cognitive perspectives on conceptual understanding share common principles. Scott, Asoko, and Leach (2007) summarize the common characteristics of cognitive approaches to conceptual change as:

1. Individuals’ beliefs about the natural world are constructed, rather than received.
2. There are strong commonalties in how individuals appear to think about the natural world
3. A person’s existing ideas about a given subject greatly influence his/her subsequent learning about that subject (p. 39).
From these common principles, the roles of students and teachers and instructional materials can be derived. Students are active participants in the learning/teaching process, and they construct their conceptual understanding through the guidance of their teacher. In this process, they use their existing knowledge as a ground for their conceptual framework. Teachers are active members of the learning/teaching process as well; however, their role is to provide scaffolding and guidance for students, rather than to impose and transfer knowledge.

**Summary of the Literature Review**

The purpose of this study is to suggest that LEGO™-based, engineering design activities can be used as a context for science instruction, and that engineering-design activities have a potential to address the multiple challenges that educators face in their attempt to improve students’ achievement in science and to increase their motivation and interest in science learning and improve their technological (engineering) literacy. While the existing studies in the literature make valuable contributions to the teaching and learning of science and technology, a clear next step is to investigate the impact of LEGO™-based, engineering-design practices on students’ science content learning and how the characteristics of the engineering-design curriculum support students’ ability to learn the science of simple machines and support students in changing their misconceptions.

With this study I seek to advance theory, design, and practice in the emerging field of elementary school engineering education, in a way which I believe can motivate and deepen the learning of science. This study will make a contribution to the existing
body of literature by addressing the impact of LEGO™-based, design-oriented practices on students’ science content learning and to the particular literature by addressing the inner dynamics of engineering-design practices during instruction. Thus, the results of this study will enable science educators to harness the engineering design process for more effective science instruction.
CHAPTER 3. METHODS

This study employed a mixed methodological approach in order to investigate how LEGO™ engineering-design curriculum materials, in contrast to inquiry-based curriculum materials, may improve students’ understanding of science content and help them establish their conceptual framework about simple machines. I am interested in how LEGO™ engineering-design practices in contrast to inquiry activities, affect students’ learning and how young people learn in both types of curricula. Specifically the driving questions of this study are:

a) What do students learn about the science of simple machines in a LEGO-engineering design unit, in contrast to a scientific inquiry-based unit?

b) How do the characteristics of these curricula support students’ ability to learn the science of simple machines and help them correct their misconceptions?

A mixed methodological approach was used to investigate these topics. Johnson and Onwuegbuzie (2004) define the mixed-method study as a single approach that integrates both quantitative and qualitative stages of data collection, analysis, and interpretation. There are numerous advantages of using a mixed-method approach for this study. These advantages include having different perspectives with each method, being able to gather more in-depth information, and being able to ensure reliability.

Denzin and Lincoln (2008) state the advantage of using more than one interpretive practice as follows: “… each practice makes the world visible in a different
way. Hence, there is frequently a commitment to using more than one interpretive practice in any study” (p. 5). In accordance with this statement, quantitative methods such as written tests enabled me to assess the students’ knowledge of scientific concepts before and after instruction. In addition, qualitative methods, such as interviews and observations, provided me with insights about how the students make sense of phenomena, how they think, and why they think the way they do.

The goal for selecting a mixed methodological approach is to draw from the strengths and minimize the weaknesses of single-method research studies. As cited in Denzin & Lincoln (2008), Tashakkori & Tedllie (2003, p.15) divide inquiry into two categories: exploration and confirmation. They assign qualitative research to exploration and quantitative research to confirmation. Thus, a mixed methodological approach gives the researcher opportunities to explore the research questions as well as to confirm them.

Additionally, Lincoln and Guba (1986) suggest triangulation as one way to increase the reliability of the researcher’s interpretations. In this study, the data were triangulated through multiple sources, including direct observations, interviews, and written tests (including both multiple choice and open-ended questions).

My vision of using a mixed methodology aligns with Denzin and Lincoln’s (2008) statement, “No specific method or practice can be privileged over any other” (p. 9). I believe that neither quantitative data-collection methods, nor qualitative data-collection methods are superior to the other. Instead, qualitative and quantitative methods, especially in this study, supplement each other. For example, quantitative data collection methods such as written tests and interviews will help me understand what
students learn in each of the curricula, while qualitative data collection methods such as observation videos will help me define the characteristics of each curriculum and understand how teachers enact those characteristics in their classroom.

Finally, a mixed-methodology appears well-suited to situated cognition. Vygotsky (1978), one of the founders of situated cognition and learning with activity, argues that psychological and cognitive processes emerge in contextualized, holistic activities that include organic and functional relations between individuals and the society. Similarly, Greeno (2006) defines activity systems as “complex social organizations containing learners, teachers, curriculum materials, software tools, and the physical environment” (p.79). Therefore, both quantitative and qualitative methods may be used to measure and describe such complex processes, in order to understand the multifaceted causal relations and correlations in those processes.

The Theoretical Basis for Conceptual Understanding

My notion of teaching and learning in science education corresponds with the knowledge in pieces theory. diSessa (1988, 1993) argues that the human brain stores knowledge in pieces that reflect very basic and simple relations. He calls these pieces “phenomenological primitives” or “p-prims” (diSessa, 1993). As followers of the knowledge in pieces theory, Southerland, Abrams, Cummins, and Anzelmo (2001) give clear definitions of phenomenological primitives (p-prims). They argue that p-prims “are understood to be atomistic knowledge structures that are automatically and unconsciously activated by the learner in response to a particular situation” (p. 329). They also adopted Ueno’s (1993) definition that “p-prims are fundamental pieces of knowledge that are
understood by the learner to need no explanation, as they operate as implicit presuppositions of how the physical world works” (p. 329-330). P-prims can be viewed as the building blocks of conceptual structures. When students are asked to explain a scientific phenomenon, they organize the p-prims that they already know with their experiences and logic. In a sense, they create a pattern by knitting together the p-prims.

In general, students who gather knowledge by rote memorization cannot store this information in their long-term memory (Novak, 1993). Therefore, they often lack an understanding of how small pieces of knowledge connect and contribute to each other and form a meaningful conceptual picture (di Sessa, 1988; Ebenezer, 1992). However, hands-on design experiences require connecting pieces of knowledge to each other with meaningful relations and organizing this knowledge on a wide-scale by forming a conceptual framework. This conceptual framework then serves as the theory behind their design.

Smith, diSessa, & Roschelle (1993/94) argue that conceptual change is a knowledge refinement and reorganization of pieces of knowledge. They see students’ preconceptions as useful for instruction to reorganize and refine their knowledge. Similarly, Osborn & Wittrock (1983) define learning as a generative process and argue that students construct knowledge during cognitive processing. Clement (1993) emphasizes that not all preconceptions are misconceptions. He states, “Such conceptions should be respected as creative constructions of the individual, and in some cases they are successful adaptations to practical situations in the world” (Clement, 1993, p. 1241). Minstrell (1982) investigates the various facets of
students’ knowledge. He argues that students’ knowledge is in pieces that he called “facets”, and the students use these pieces in a learning situation to construct an understanding of the phenomena. Minstrell argues that “[conceptual] change will involve the addition of facets based on concrete experience. As more and more concrete knowledge is gained through experience, the facet may become grouped with additional qualifier facets that help define appropriate contexts of application” (Minstrell, 1982, p. 120). He also suggests that diagnosing students’ knowledge facets can be helpful in designing quality instruction materials. By engaging students in real-life, hands-on design situations, students will be able to gain experience of nature and its rules. In the end, these experiences will help them construct appropriate conceptual understandings of scientific phenomena.

Hunt and Minstrell (1994) attribute to physics a central role in science and engineering because they see physics as an important gateway to other subjects in science and engineering. They found diSessa’s (1988) knowledge in pieces theory an appropriate way to explain students’ cognitive structures for understanding physics. By using their own term, facet, for diSessa’s p-prims, they give examples of students’ knowledge in pieces. For example, when students think of a paper plane, they may adopt the facet “Horizontal motion slows vertical motion” since they may have had real-life experiences that support this facet. However, this facet does not take into account the effects of the surrounding fluid medium of air (Hunt & Minstrell, 1994).
Characteristics of the Curricula

The design-based LEGO™ simple machines unit and inquiry-based Full Option Science System (FOSS) simple machines unit have different characteristics as well as shared characteristics. The inquiry in this study includes investigation of whether those characteristics of the curricula are implemented and how they help students to understand science and improve their conceptual understanding of simple machines. Thus, those characteristics and features of each curricular unit will be defined. First, I explored the design-based LEGO™ simple machines unit and how it is developed. Second, I explored the FOSS levers and pulleys unit and its characteristics.

The Design-Based LEGO™ Simple Machines Unit

Conceptual Frame of the Design-based Curriculum. The Design a People Mover: Simple Machines unit incorporates three approaches to design-based science instruction at the elementary and middle school level in the United States: design-based modeling (Penner, Giles, Lehrer, & Schauble, 1998), engineering for children (Roth, 1996), and Learning by Design™ (Kolodner, 2006). These approaches are chosen because their theoretical background, principles of curriculum design, and findings on learning are all available for review and they are representative of the field (see Wendell, Connolly, Wright, et al., 2010 for a detailed review).

In the ‘Design-Based Modeling’ approach, Penner and his colleagues interpreted design-based instruction from a modeling perspective for early elementary students (Penner, Giles, Lehrer, & Schauble, 1997; Penner, Lehrer, & Schauble, 1998). Through
this approach, students build, test, and evaluate models. In their study, they asked grade 1-2 students to design models of the human elbow. They used biomedical models of human arms as a context to engage students in an investigation of leverage and the relations between the force and fulcrum. Students were able to understand the relation between mathematics and science through their experience with the use of data tables and graphs to understand phenomena. Penner et al. (1997, 1998) support the claim that, with appropriate scaffolding, students can understand how artifacts and mathematical inscriptions, such as data tables and graphs, can be utilized as evidence that scientists use in scientific discourse. At the same time, students’ design skills could be improved as well. On the other hand, Penner et al. (1997, 1998) realized that helping students to understand explicitly the key scientific process, rather than memorizing patterns of artifact building, is not an easy task.

In the engineering for children (Roth, 1996, 1997, 2001) approach, Roth worked with 9- to 12-year old elementary students on designing a sturdy tower to teach stability, shapes, and forces and on building a machine that uses simple machines for teaching the physics of simple machines. Roth (1996, 1997, 2001) reported the six potential learning areas with the engineering for children approach as: (a) dealing with complex, open-ended tasks, (b) discovering new meanings for materials and artifacts, (c) being conscious of participation in design, (d) negotiating with classmates, (e) using a variety of tools in interesting ways, and (f) communicating about design. The main contribution of this approach is its emphasis on classroom discourse (talking and writing), and its argument that discourse is as important as design for learning science. For Roth, the challenges for
implementation of this approach include ambiguity in its instructional sequence, uncertainty in the definition of what constitutes a good design task and teacher interference in its effectiveness.

In the Learning by Design™ (LBD) approach, Kolodner and her colleagues worked with middle school students on designing an optimal balloon-powered coaster car for teaching basic mechanics and Newton’s laws of motion (Kolodner et al., 2003; Kolodner, 2006). LBD students showed higher gains than matched peers in both conceptual learning and process-oriented skills such as designing experiments, planning data collection, and collaborating. Kolodner and her colleagues recognized that classroom culture is an important factor for the success of LBD activities (Kolodner et al., 2003; Kolodner, 2006). Since classroom culture that is conducive to design is not created automatically, they specified “ritualizing practices” to help construct the optimal culture. Like Roth (1996, 1997, 2001), Kolodner and her colleagues emphasized the dependence of the success of LBD activities on teacher competency and attitudes (Kolodner et al., 2003; Kolodner, 2006).

A variety of science content areas have been addressed using these three approaches to design-based science instruction. The design tasks chosen to situate the science content also span a wide range. In addition, all three of these approaches understand design as an activity whose goal is the construction of a physical product. In all of these approaches, students are initially tasked with creating a functioning device or system that serves a purpose established by the instructor. The resulting construction is then considered an essential factor in students’ learning. For Penner et al. (1997; 1998),
the designed constructions enable model-based reasoning, deeper investigation of science concepts, and the exploration of mathematical relationships. Roth (1996) sees each design construction as a tool to think with, a representation of cognitive processes, and a backdrop for class discussion and sense-making. Finally, in Kolodner’s work (2006), the challenge of creating a functioning product provides motivation and opportunities for scientific reasoning and learning.

Across these three approaches, there are several commonalities in how classroom instructional practice is structured. In all these studies, students work in groups, and interaction among students and improvement of communication skills are key goals of the teacher. As they work on solving the design problem, students are always expected to engage in written or pictorial record-keeping. At some point, students are given the option to revise their designs. In addition to their individual record-keeping and reflection, students reflect on their design through participation in whole-class discussions. Importantly, throughout design-based science units, teachers provide guidance on how students should incorporate scientific ideas and careful reasoning into their design solutions. Researchers believe that this scaffolding is essential for preventing students from merely tinkering.

**Background: Overview of the Larger Curricular Project.** This study is a subset of a larger research project named “Transforming Elementary Science Learning through LEGO™ Engineering Design (TESLED)”, an NSF-funded project supported by the Research and Evaluation on Engineering and Science Education (REESE) program. For the purposes of the project, four design-based elementary science curricular units
have been developed and implemented. These curricular units include (a) *Design a Musical Instrument: The Science of Sound*, (b) *Design a Model House: The Properties of Materials*, (c) *Design an Animal Model: Animal Studies*, and (d) *Design a People Mover: Simple Machines*. These general topics were chosen in consultation with our school partners.

The purpose of the larger project is to investigate the impact of using engineering-design-based activities as contexts for specific science content instruction in the upper elementary grades. To explore this question, we have collaborated with local teachers to develop and implement four engineering-design-based science curricula for third, fourth and fifth grade classrooms. In engineering-design-based science, students engage in scientific investigations to deepen their understanding of a design problem’s constraints and potential solutions. The process of solving the design problem provides opportunities for students to learn and apply new science concepts and practices as well as to refine their existing science concepts. For example, to tackle the design challenge of constructing a lever, students must understand the relationship between load and effort as well as the relationship between the load arm and the lever arm.

**Overview of the Curriculum Program.** The four curriculum units that we have developed are intended for third, fourth and fifth grade (8- to 11-year-old) students. Each unit poses an overarching engineering design challenge as a motivator for science investigations and uses interlocking (LEGO™) construction elements for prototyping. It also requires approximately 12 hours of instructional time and addresses a particular science domain. The *Design a Musical Instrument* unit centers on the science of sound,
Design a Model House focuses on the properties of materials and objects, Design an Animal Model emphasizes the structural and behavioral adaptations of animals, and Design a People Mover focuses on the force-distance trade-offs of simple machines. The units’ learning objectives are aligned with the local and national standards of science learning.

Common aspects of all units. To begin a unit properly, teachers enact two introductory lessons that are the same for all four units. The goal of these preparatory lessons is to introduce students to engineering and learning with LEGO™ materials. After sharing their initial ideas about what engineering is, students are presented with a definition of engineering and a five-step model of the engineering design process (see Figure 2). Next, they are invited to classify items as “engineered” (e.g., a light bulb) or “probably not engineered” (e.g., a tree). Finally, they are given time to explore basic LEGO™ construction techniques. After these experiences, teachers launch into one of the science curriculum units. Each science unit follows approximately the same instructional pattern, which entails a series of 9 to 11 lessons that are designed to require one hour of instructional time.

Common materials for all units. Teachers and students are provided with the same general set of tools for each unit. These include a) a teacher’s guide, b) an Engineer’s Journal (for students), c) a written science content assessment, d) an assortment of common craft materials, and e) a kit of LEGO™ construction elements and electronic sensors for each student pair. The assessment will be discussed in a later section; the other tools are described below.
The teacher’s guide is intended both to specify lesson enactment and to support growth in the teacher’s science and pedagogical content knowledge. For each lesson, the guide includes eight sections: learning objectives, background information about the science content, typical preconceptions held by students, key vocabulary terms, materials to be gathered, preparation steps to be taken before the lesson, procedure for instruction, and tips for assisting students with building and testing.

The student Engineer’s Journal is a paper-and-pencil tool that guides the students through the unit’s engineering design process. For each of the nine to eleven lessons in a unit, the journals provide introductory open-response questions, building and observation instructions, data recording prompts, and reflection questions. The prompts and questions ask for writing, drawing, and numerical inscriptions, and each of these activities provides an opportunity for students to record their emerging content knowledge and to practice skills related to the unit’s science domain.

The rationale for using a combination of LEGO™ tools and craft materials, instead of craft materials only, is that the interlocking building elements in the LEGO™ toolset have a low “cost” of prototyping and re-design (Bers, 2008). Because the LEGO™ elements do not require any assembly tools (such as glue, tape, staples, or scissors) students can quickly create a first prototype. Also, unlike glue, tape, or staples, the fastening mechanisms for LEGO™ pieces are sturdy but always temporary, so students can quickly reverse an action and move pieces around to change a design. Another reason for selecting the LEGO™ toolset is that its building elements are compatible with microprocessors and electronic sensor probes. This allows for the
interweaving of design challenges and science investigations. Finally, the LEGO™ toolset is a one-time investment that lasts for many years without the need for re-supply, and LEGO™ materials are perceived by students to be a novel and motivating tool for science learning (Cejka, Rogers, & Portsmore, 2006).

In the curriculum development process, triarchic teaching and assessment methods (Grigorenko, Jarvin, & Sternberg, 2002) are integrated with design-oriented instruction and LEGO™ engineering tools. The theoretical framework for the curriculum intervention is based on the notion that engineering design is a natural pathway for “triarchically based” instruction and assessment, which has been shown to improve student achievement as compared to conventional instruction (Grigorenko, et al., 2002; Sternberg, Grigorenko, & Jarvin, 2001). By integrating triarchically-based instruction, analytical, creative, and practical thinking and learning skills, in addition to traditional memory skills, are involved in the curriculum and assessment development processes.

In this study, I focus on the Design a People Mover: Simple Machines unit as an instrument for teaching specific science content, namely simple machines. This unit, like the other units, was developed by a team of researchers from Boston College and Tufts University. The research team consists of two faculty and three graduate students from Tufts University and one faculty and one graduate student from Boston College. In terms of expertise, the team compromised a number of professionals from different fields. The faculty included a science educator, a mechanical engineering and engineering educator, and a psychologist, while the graduate students included a physics teacher, a mechanical and aerospace engineer, an architect, and an electrical engineer.
Design and the Learning Goals of the Design-Based LEGO™ Simple Machines Unit. In 2007-08, objectives and specific lessons for the science unit on simple machines were developed by a collaborative research team. The objectives were created to encompass both the Massachusetts and national science benchmarks relevant to the science topics covered. Multiple researchers discussed and edited the objectives. The objectives were written to cover both the science concepts and the engineering design principles employed in the lessons. After these learning goals were determined, LEGO™ engineering curriculum activities that incorporated all objectives were created. Curriculum activities included teacher lesson plans, science content overviews, and student engineering journals/worksheets. Several researchers worked together to develop and appropriately modify curriculum activities before piloting them. From February to June 2008, these lesson plans were pilot-tested by researchers in a local fourth-grade classroom. The collaborating teacher offered feedback after each lesson. During June 2008, both modules were revised and compiled into teacher guides and student journals. Since September 2008, the unit has been implemented in Boston area schools and has gone through a continuous development process.

In this LEGO™-based, engineering-oriented simple machines curricular unit, engineering design is embedded in the curriculum as an essential theme. It does not, however, consist of only engineering design activities. The unit includes inquiry themes as well as design themes. This unit is designed to engage students in engineering-design processes with the end goal of solving real life problems while engaging students with basic scientific content.
The *Design a People Mover: Simple Machines* unit includes eleven lessons, each of which is designed for a 60 minute period. An example of a lesson plan and engineer’s journal is given in Appendix C. Through the lessons in the unit, students investigate each type of simple machine by building a LEGO™ version and then using it to accomplish some physical task. With each simple machine, they explore the design trade-off between reducing force and increasing distance. The final design challenge of this module is to combine multiple simple machines into a complex LEGO™-person-mover machine that can move a LEGO™-man six inches up and eighteen inches across. To accomplish this task, students are required to use at least three simple machines in their design, and they are allowed to touch their complex machine once to initiate the task.

**The Design a People Mover: Simple Machines (Experimental) Unit.** The Design a People Mover: Simple Machines unit includes a series of eleven lessons. Each individual lesson is designed to follow a similar flow of events. First, the teacher initiates each lesson by describing the task of the inquiry (mini-challenge or mini-investigation) to be completed for that day. Then students work independently for five minutes in response to a brief brainstorming prompt – called an exploration question – related to that goal. After having a short whole-class discussion about the exploration question, students work in pairs on the mini-challenge or mini-investigation. Instructions for building and prompts for testing and observing are provided in their Engineer’s Journal. The lesson concludes with a teacher-led, whole-class discussion about how the lesson’s experiences provided new knowledge or skills that will be useful for the grand design challenge. The overview of the Simple Machines: Design a People Mover unit is given in Appendix B.
As illustrated in Figure 2, the unit pattern roughly approximates one cycle through the engineering design process. The engineering design process consists of five steps: finding a problem, researching possible solutions, choosing the best solution, building a prototype, and testing the prototype.

![Diagram of the engineering design process](image)

**Figure 2.** Instructional pattern for our Science through LEGO™ Engineering units, compared to a simplified model of the engineering design process (Wendell et al., 2010). Reprinted with permission.

**Find a Problem.** The “find a problem” step occurs first; the first lesson in the unit focuses on specifying the grand engineering design challenge and the big science question for the unit. The aim of the lesson is that students will:

- Define engineering design as the process of creating solutions to human problems.
The grand design challenge for the unit is building a people mover that moves people up and over. Figure 3 displays the introduction of the final design challenge in the student’s journal. In lesson 1, students write down what knowledge they already have to help them complete the challenge and answer the question, and identify what they still need to learn. Then students are invited to brainstorm and to sketch their initial ideas about the grand design challenge.

**Research Possible Solutions and Choose the Best Solution.** The next two steps of the engineering design process are “research possible solutions” and “choose the best solution”. These two steps are nested in the next seven lessons, where students carry out “mini design challenges” and “mini science investigations” to acquire the knowledge and skills that will enable them to succeed in the grand design challenge. Most of the mini
challenges and investigations involve the construction and testing of physical artifacts. Through these challenges and a series of investigations, students develop their science knowledge and skills. Students also have an opportunity to apply their findings to potential design solutions and choose the best solution.

The aim of the lesson 2 is that students will:

- Explain that simple machines help humans; more specifically, recognize that simple machines help humans by: (a) decreasing the input force and increasing the input distance or (b) increasing the input force and decreasing the input distance needed to do work. Simple machines do not change the amount of work done.
- Define engineering design as the process of creating solutions to human problems through creativity and the application of math and science knowledge.

In lesson 2, the students are invited to discuss how machines help humans. The seven simple machines are introduced to students, and students explore examples of all different types of simple machines. The teacher prepares seven stations including in each different real-life objects that are representatives of a simple machine. Students visit those stations and predict what simple machine the objects in each station represent. Students record their prediction in their engineer’s journals. Then in a whole-class discussion, for each station, the teacher has students identify the similarities among all the items, and discuss how those similarities might be clues that indicate the set’s simple machine category. Finally, the teacher reveals the scientific name of the simple machine
that the set belongs to, and have the students write it down on their Simple Machines data table.

The aim of lesson 3 that students will:

- Explain that levers are stiff bars that rotate around fixed points, and they help humans by making it easier to lift a load or apply a force.

In lesson 3, students start learning individual simple machines. In this lesson, students are introduced to the mechanics of levers and the ways levers can help humans. Students are introduced to key lever vocabulary (load, force, distance, rotation point) through the demonstration of a prying lever and the investigation of a weight-lifting lever. By using LEGO™ materials, students build three levers with a different fulcrum point for each.

Figure 4. Three levers with different fulcrum points.

Figure 4 displays three levers with different fulcrum points. Students attach a weighted brick to the left end of each lever arm. Then they compare the force they have to use to lift the load with the distance they move the right end of each lever to lift the load to the same height as the top of the L-beams. As shown in Figure 5, students record their observations about the force and distance needed to lift the load for each lever. Through these observations, the aim is that students will understand the relation between the force needed to lift a load and the distance that the load is lifted up.
The aim of lesson 4 is that students will:

- Explain that levers are stiff bars that rotate around fixed points, and they help humans by making it easier to lift a load or apply a force.
- Identify examples of simple machines (levers) in everyday objects.
- Identify simple machines (levers) within complex machines.

In lesson 4, students are introduced to the mechanics of two-armed levers and the ways they can help humans. They have a class discussion about how changing a lever’s
rotation point affects the applied force and distance. They compare and contrast common levers (such as staplers, kitchen tongs, bats) and brainstorm everyday examples of levers. At the end of lesson 4, students are again asked to sketch their ideas about the people mover and explain their ideas in writing.

The aim of lesson 5 is that students will:

- Explain that wheel-and-axles are two differently-sized wheels attached to the same axis, and they are used to make circular motion easier (Wheels are circular rotating objects that make moving other objects easier. Axles are linear bars that connect together with wheels to move other objects more easily).
- Identify examples of simple machines (wheel-and-axles) in everyday objects.
- Identify simple machines (wheel-and-axles) within complex machines.

In lesson 5, students are introduced to the uses of wheels and axles and the ways wheels and axles can help humans. They are invited to think about common uses of wheels and axles and how wheels and axles can be used to move objects. They build a model of a wheel-and-axle and distinguish the wheel and the axle part of the mechanism.

In this lesson, students build a miniature food mixer to investigate how an object with a wheel-and-axle system helps us do work. Figure 6 shows a Lego™ miniature food mixer that students built in this lesson.
Once students are done building their food mixers, they are invited to test out four different designs for using the food mixer. Figure 7 displays the chart that is provided for students to record their investigations about different designs of food mixers. The first three food mixer designs are pre-determined; however, the fourth design is left for students to create. In this investigation, students are to record and then compare the amounts of force it takes to mix the food with different food mixers. They also need to record and compare how big of a circle the handle needs to be turned. Through this investigation the aim is that students will learn that there is a trade-off between force and distance in wheels and axles like other simple machines. Finally, since students have learned about another simple machine, they are again asked to sketch out and explain by drawing and writing their ideas about the final design challenge.

Figure 6. A LEGO™ miniature food mixer that students built in lesson 5.
**INVESTIGATION INSTRUCTIONS**

**STEP 1.** Test out four different designs for using the food mixer to mix up the food. Be sure to fill out the two observation columns for each test. The pieces needed are shown here and the completed designs are shown in the chart below.

<table>
<thead>
<tr>
<th>Handle</th>
<th>5-hole beam</th>
<th>15-hole beam</th>
<th>Long Connector Peg</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Observations</th>
<th>Turning Design</th>
<th>How much force does it take to mix the food? (a little, a medium amount, or a lot?)</th>
<th>How far a distance (or how big of a circle) does the handle need to be turned? (shortest, medium, longest)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axle Only</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Short Handle (Handle, 5 Hole Beam)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long Handle (Handle, 15-Hole Beam)</td>
<td></td>
<td></td>
<td>LEGOs building note: Slide the axle through the LEGO handle. Attach the beam to the axle and peg on the handle. Insert a long connector peg into the end of the beam.</td>
</tr>
<tr>
<td>Your Own Design</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Figure 7.* Recording chart for testing out different LEGO™ miniature food mixer designs.

The aim of lesson 6 is that students will:
• Explain that inclined planes are surfaces slanted upward, and that they lower the effort needed to lift a load.

• Explain that wedges are two inclined planes joined back to back to form a sharp edge, and they are used to change the direction of a force and often result in the splitting of objects.

• Explain that screws are inclined planes wrapped around a cylinder, and they are used to raise and lower objects and hold objects together.

• Identify examples of simple machines (inclined planes, screws, and wedges) in everyday objects.

• Identify simple machines (inclined planes, screws, and wedges) within complex machines.

In lesson 6, students are introduced to the uses of inclined planes, screws, and wedges and the ways these simple machines can help humans. They test steep and gentle inclined planes to determine which requires the least force. They investigate the inclined planes in screws and wedges and find screws and wedges in everyday objects. In this lesson, students are introduced to the use of spring scales for measuring force. Students build a Lego-cart to carry weight. They measure the force needed to carry this cart and weight up to the top of the Lego box without using inclined planes, using a steep inclined plane, and using a gentle inclined plane. They also record the distance they traveled when they reach the half way height to the Lego box for each condition. They record their measurements on a table (Table 2) and compare the forces needed and the distances traveled in each condition. Finally, since students have learned other about other simple machines, they
are again asked to sketch out and explain by drawing and writing their ideas about the final design challenge.

Table 2

*Comparing the distance traveled and the force needed to lift an object without a ramp, with a steep ramp and with a gentle ramp*

<table>
<thead>
<tr>
<th></th>
<th>Straight Up - No Ramp</th>
<th>Steep Ramp</th>
<th>Gentle Ramp</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lifting Force</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Newtons)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Distance Traveled</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(cm)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The aim of lesson 7 is that students will:

- Explain that pulleys are wheels with grooved edges for ropes, and that they are used to change the direction of a pull and make it easier to lift a load.

In lesson 7, students are introduced to pulley systems as a means for lifting heavy things to heights above their heads. Students explore LEGO-sized fixed pulley and moveable pulley systems and observe the force and distance required for full-sized fixed pulley and
moveable pulley systems as demonstrated by their teacher. Figure 8 shows the
demonstrations that display the use of a fixed pulley and a moveable pulley.
Moveable Pulley Set-Up

- Rope is tied to fixed pulley OR to ceiling/wall.
- One pulley remains tied to ceiling or wall.
- Load is lifted until the pulley wheels touch.
- Distance moved by the load.
- Pulling distance.

START

One pulley (with load tied to it) is moveable and balanced on rope.

Finish

Load is resting on table or ledge and is tied to moveable pulley.

Fixed Pulley Set-Up

- Pulley is tied to ceiling or wall.
- Load is lifted to fixed pulley wheel.
- Distance moved by the load.
- Pulling distance.

START

Load is resting on table or ledge.

Finish

With the load hanging freely (not resting on or against anything), use the 5-Newton spring scale to measure the pulling force. Make sure you hold your hand still as you read the meter.
Figure 8. Demonstration of a fixed pulley system and a moveable pulley system.

After watching their teacher demonstrate fixed and moveable pulleys, students build Lego™ pulley systems as shown in Figure 9. Students measure the pulling force and the pulling distances by using these pulley systems and make comparisons between them. Students first compare a small pulley with a bigger pulley as fixed pulleys. Then they compare fixed pulleys with moveable pulleys. The aim is that these activities students will understand that fixed pulleys help people by changing the direction of force, that moveable pulleys help people reduce the force needed to pull up a weight with an exchange of more distance, and that the size of the pulley does not make any difference.

Figure 9. LEGO™ fixed and moveable pulley systems: (a) a small fixed pulley, (b) a big fixed pulley, (c) a moveable pulley.

The aim of lesson 8 is that students will:
• Explain that gears are wheels with teeth around the edge, and that they are used to turn other gears and change the direction, speed, and force of circular motion.

In lesson 8, students are introduced to the uses of gears and the ways gears can help humans. Students build a gear train as shown in Figure 10. Students turn the gear train by using different gears as the driving gear and compare the force needed to turn each gear and the distance they need (or the number of turns) to lift the weight.

![Gear train for lifting a weight.](image)

*Figure 10. Gear train for lifting a weight.*

In addition, students build different variations of two or three gear trains by using different size gears and answer short-answer questions about them as shown in Figure 11. Through these activities, the aim is that students will learn the functions of gears and their
force-distance trade-offs. They also develop an understanding of how gears can be used to change the direction and speed of motion. After students learn about the functions of gears and the advantages of using them, they are invited to solve a design challenge: build a gear train that will spin a disk fast enough to create an optical illusion.

<table>
<thead>
<tr>
<th>Gear Train</th>
<th>Circle the answer to complete the sentence.</th>
</tr>
</thead>
</table>
| ![Gear Train](image1) | When the first gear turns right.
the second gear turns: left right
The gears turn at different speeds. |
| ![Gear Train](image2) | When the first gear turns right.
the second gear turns: left right
the third gear turns: left right |
| ![Gear Train](image3) | The big gear turns faster than the small gear. |
| ![Gear Train](image4) | The small gear turns faster than the big gear. |
| ![Gear Train](image5) | The big gears turn at the same different speeds. |
| ![Gear Train](image6) | The fastest gear is the smallest medium largest
The slowest gear is the: smallest medium largest |

*Figure 11. Different variations of gear trains and short-answer questions about them.*
Choose the Best Solution. After completing the “research possible solutions” step of the engineering design process, students go through the “choose the best solution” step. In this step, students learn how to use their findings and choose the best solution to solve a design challenge.

The aim of lesson 9 is that students will:

- Identify simple machines within complex machines.

In lesson 9, students are introduced to how simple machines can be put together to make complex machines. Students start the lesson by exploring the differences between simple and complex machines. They are asked to discuss the differences between simple and complex machines with their partner and then to write and draw their ideas in their Engineer’s Journal. After having a whole-class discussion about the exploration question, students are provided with pictures of four complex machines (a pair of scissors, a pencil sharpener, a crane and a can opener) and are asked to find the simple machines in these complex machines.

Then students review force-distance trade-offs for each simple machine. The chart that is shown in Figure 12 is given to students to have them work through the trade-offs of each simple machine. In this chart, two different designs of each simple machine are displayed. Students are asked to choose the design that lets them put in less force for each simple machine and explain the trade-off for putting in less force. After filling out the trade-off chart, students are asked to brainstorm independently and sketch ideas about the design of a people mover. Then they share ideas with their partner and choose the best idea, perhaps by combining different ideas into one sketch. This sketch is used as the
basis of their final design. Unless students show the teacher their completed design ideas, they cannot retrieve their LEGO kits to begin building.

<table>
<thead>
<tr>
<th>Simple Machine</th>
<th>“Design Rules of Thumb”</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Which design lets you put in less force?</td>
</tr>
<tr>
<td>Lever</td>
<td>![Image of Lever]</td>
</tr>
<tr>
<td>Inclined Plane</td>
<td>![Image of Inclined Plane]</td>
</tr>
<tr>
<td>Screw</td>
<td>![Image of Screw]</td>
</tr>
<tr>
<td>Wedge</td>
<td>![Image of Wedge]</td>
</tr>
<tr>
<td>Pulley</td>
<td>![Image of Pulley]</td>
</tr>
<tr>
<td>Gear</td>
<td>![Image of Gear]</td>
</tr>
</tbody>
</table>

*Figure 12. Simple machines’ trade-off chart.*
Build a Prototype and Test the Prototype. Finally, the “build a prototype” and “test the prototype” steps take place in the last two lessons of the unit. After sketching out their best solutions to the final design challenge, students build a prototype of their design. Students test and improve their solutions to the grand design challenge, rebuild if necessary and then present to their classmates an explanation of how their solutions work.

The aim of lesson 10 is that students will:

- Identify simple machines within complex machines
- Choose the best simple machines to incorporate into a design to address a problem

In lesson 10, students work together with their partner to build their LEGO-person-moving complex machine. They test their machine, and if it doesn’t work, they re-design, re-build, and re-test until it does. Once students have their machines working the way they want them to, they fill out a rubric to evaluate their people-mover complex machine.

The rubric for evaluating the final design is shown in Figure 13. This rubric evaluates whether or not students’ people movers meet the final design challenge rules. Then students are asked to draw an engineering diagram of their people-mover machine and label the simple machines within their complex machines.
Figure 13. The rubric for evaluating students’ people mover complex machines.

The aim of lesson 11 is that students will:

- Identify simple machines within complex machines
- Choose the best simple machines to incorporate into a design to address a problem

In lesson 11, students present their complex machines to other students and review other students’ machines. Students record what simple machines they used and their peers used, to move the person up and across. Then the teacher facilitates a culminating class discussion in which students reflect on their learning about simple and complex machines. Finally, the teacher and students identify how simple machines help us in a whole-class discussion. The teacher provides the chart shown in Figure 14. She gathers students’ ideas about which simple machines belong in each column, and asks students to explain their reasoning scientifically.

<table>
<thead>
<tr>
<th>Simple machines that help to <strong>split or cut:</strong></th>
<th>Simple machines that help to <strong>change direction:</strong></th>
<th>Simple machines that help to <strong>change speed:</strong></th>
<th>Simple machines that help to <strong>change amount of needed effort:</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Figure 14. The chart that was given to students to identify how simple machines help us.*

**The Inquiry-based Simple Machines (Comparison) Unit**

The Full Option Science System (FOSS) program started as a science enrichment program at the Lawrence Hall of Science twenty years ago. Since then, the program has evolved with the support of the National Science Foundation and the University of California at Berkeley and has become a total curriculum for K-6 students and teachers.
The FOSS curriculum is designed as an inquiry-based curriculum. Modeled on the activity of practicing scientists, the two main questions the FOSS curriculum seeks to answer are “what is in this world” and “how does it work” (p. 5-6, Lawrence Hall of Science, 2005). The FOSS curriculum uses several instructional pedagogies to make science teaching and learning more efficient and productive (p. 6, Lawrence Hall of Science, 2005). These pedagogies include inquiry, hands-on-active learning, multisensory methods, student-to-student interaction, discourse and reflective thinking, and reading and research.

The control group was taught simple machines using the Full Option Science System’s (FOSS) inquiry-based *Levers and Pulleys* unit which is designed for fifth and sixth grades. The unit aims to introduce students to the key concepts of simple machines with four investigations: *levers, more leverage, pulleys and pulleys at work*. The module matrix of the *Levers and Pulleys* unit, in which a summary of the unit is provided in a matrix format, is shown in Figure 15.
**LEVERS AND PULLEYS MODULE MATRIX**

<table>
<thead>
<tr>
<th>LEVERS</th>
<th>SCIENCE CONTENT</th>
<th>THINKING PROCESSES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Students are introduced to levers as devices that help lift weight or overcome resistance. Students investigate the fulcrum, effort, and load of one kind of lever (class-1) and conduct experiments with a spring scale to determine the relationships between the parts of a lever system. They draw and graph their results.</td>
<td>A lever is a simple machine that people use to gain an advantage, such as making work easier.</td>
<td>Measure the effect of lifting a load when the load remains constant and the effort changes position.</td>
</tr>
<tr>
<td>2. MORE LEVERAGE</td>
<td></td>
<td>Measure the effect of lifting a load when the effort remains stationary and the load moves.</td>
</tr>
<tr>
<td>Students investigate and diagram class-1, class-2, and class-3 lever systems. They investigate and diagram common tools to determine how the tools apply levers.</td>
<td>A class-1 lever has the fulcrum between the load and the effort.</td>
<td>Observe the behavior of different kinds of levers.</td>
</tr>
<tr>
<td>3. PULLEYS</td>
<td>A class-2 lever has the load between the effort and the fulcrum.</td>
<td>Compare the effort to lift loads with different kinds of levers.</td>
</tr>
<tr>
<td>Students are introduced to a second simple machine and discover how to set up single fixed and single movable pulleys to lift a load. They use a scale to quantify effort with a single pulley system. They go on to set up and diagram multiple-pulley systems.</td>
<td>A class-3 lever has the effort between the fulcrum and the load.</td>
<td>Diagram the relative positions and sizes of lever components in different systems.</td>
</tr>
<tr>
<td>4. PULLEYS AT WORK</td>
<td>Components are operating procedures that help people communicate more efficiently.</td>
<td>Analyze work in terms of their application as levers.</td>
</tr>
<tr>
<td>Students systematically investigate four pulley systems. They record data on each system. They graph and determine the relationship between the number of dynes pulling on the load and the effort needed to lift it. They determine the distance that the load and effort travel when work is done. Students determine the advantage (and disadvantage) of different pulley systems.</td>
<td>Advantage is a gain in effort, distance, or change of direction resulting from the use of a simple machine.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A single-pulley system can be set up in two ways, fixed or movable.</td>
<td>Observe and measure the effort to lift a load with single fixed and single movable-pulley systems.</td>
</tr>
<tr>
<td></td>
<td>A single-fixed pulley system provides a mechanical advantage for the user.</td>
<td>Organize information on a data sheet.</td>
</tr>
<tr>
<td></td>
<td>A single fixed pulley system provides a mechanical advantage, but changes the direction of the effort.</td>
<td>Diagram and compare the components of four kinds of pulley systems.</td>
</tr>
<tr>
<td></td>
<td>A two-pulley system can be used with one fixed and one movable pulley.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A two-pulley system in which the effort is applied upward provides a greater advantage than one in which the effort is applied downward.</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 15.** The module matrix of the Levers and Pulleys unit.
Conceptual Frame of the Inquiry-based Curriculum. Bybee (2000) gives a historical perspective on inquiry in science education. In the late nineteenth century, Charles W. Eliot suggested including a laboratory approach in the science curriculum. During the early years of twentieth century, Dewey mentioned the abilities of inquiry, the nature of science and an understanding of a subject as three important aims of science education (Dewey, 1910). In the middle of the twentieth century, Schwab (1958, 1960, 1966) distinguished between “stable” and “fluid” inquiry by defining fluid inquiry as the invention of new conceptual structures that reform science and stable inquiry as filling in the blanks of the new conceptual knowledge structure. In the early 1980s, Hurd, Bybee, Kahle, and Yager (1980) completed the biology portion of Project Synthesis, which is a project supported by the National Science Foundation to research the status of science education in the United States. Hurd et al. (1980) reported that teachers do not use inquiry in the classroom for various reasons; however, to implement inquiry in the classroom, teachers need to understand inquiry as content. To help students understand it as content, teachers need to use inquiry as a technique to teach science to students. In the late 1980s, in Science for All Americans, which is a report produced under Project 2061, Rutherford and Ahlgren (1989) suggested the following steps of inquiry teaching:

- Start with Questions About Nature
- Engage Students Actively
- Concentrate on the Collection and Use of Evidence
- Provide Historical Perspectives
- Insist on Clear Expression
- Use a Team Approach
• Do Not Separate Knowing From Finding Out
• Deemphasize the Memorization of Technical Vocabulary (pp. 147-149)

With these suggestions, Rutherford and Ahlgren (1989) emphasize the nature of scientific inquiry in teaching science, mathematics and technology. However, most of their suggestions represent a mechanistic approach to scientific inquiry from a teacher’s perspective.

Finally, in the *National Science Education Standards* (NRC, 1996), inquiry is defined to as “the diverse ways in which scientists study the natural world and propose explanations based on evidence derived from their work [and] to the activities of students in which they develop knowledge and understanding of scientific ideas and understanding of how scientists study the natural world” (NRC, 1996, p. 23). Inquiry is the top priority both as content and as technique for teachers in the *National Science Education Standards*. For example, the top science teaching standard is “the planning of inquiry-based science programs” (p. 4), while the top professional development standard is “the learning of science content through inquiry” (p. 4). Also, one of the eight categories of the science content standards is science as inquiry. Similarly, inquiry is the top priority for students to learn in science education. For all K-12 levels “abilities necessary to do scientific inquiry [and] understanding about scientific inquiry” (p. 105) are among the science as inquiry standards. Moreover, the National Research Council provides the fundamental abilities necessary to do scientific inquiry for grades 5 to 8:

• Identify questions and concepts that can be answered through scientific investigations
- Design and conduct a scientific investigations
- Use appropriate tools and techniques to gather, analyze and interpret data
- Develop descriptions, explanations, predictions, and models using evidence
- Think critically and logically to make relationships between evidence and explanations (NRC, 1996, p. 145)

Combining the FOSS and the national standards, the developers of the FOSS curriculum defined the abilities to do and to understand scientific inquiry as follows:

- Identify questions; design and conduct scientific investigations to answer those questions
- Employ tools to gather; analyze, and interpret data.
- Use data to construct reasonable explanations.
- Develop and communicate explanations using evidence.
- Recognize and analyze alternative explanations and predictions.
- Use mathematics in scientific inquiry.
- Understand that scientists use different kinds of investigations and tools to develop explanations using evidence and knowledge.

The (FOSS) Levers and Pulleys unit is an inquiry-based unit for fifth and sixth grades. The unit aims to involve students in the key concepts of simple machines with four investigations. The developers of the unit claim that “the Levers and Pulleys module helps students to develop the skills of inquiry and controlled experimentation.” (p. 2, Lawrence Hall of Science, 2005).

**The FOSS Levers and Pulleys Unit.** A classroom set of the FOSS Levers and Pulleys kit contains a teacher guide, a teacher preparation video, equipment for eight groups of students, containing four students in each, and FOSS Science Stories Levers
and Pulleys. The FOSS curricular kit uses not only instructional tools such as pulleys, spring scales, half-meter sticks, and loads (240 g), but also daily appliances such as binder clips, rubber bands and cardboard sheets. The teacher guide includes masters’ copies of students’ Levers and Pulleys Journals as well as background information for teachers and plans for investigations.

**Investigation 1: Levers.** The aim of this investigation is that students will (a) gain experience constructing and using levers, (b) learn the concept of lever arm, fulcrum, load, and effort, (c) experience one advantage that can be gained by using a lever-reduced effort, (d) collect, organize, analyze data from lever experiments, and (e) use scientific thinking processes to conduct investigations and build explanations: observing, communicating, comparing, organizing, and relating. The science concepts that the investigation aims to teach students include: a lever is a simple machine that people use to gain an advantage, such as making work easier; an advantage is a benefit obtained by using a lever (or other simple machines); effort is the force needed to move a load or overcome a resistance; a fulcrum is the point where a lever arm pivots; and load is a mass lifted or a resistance overcome by a lever.

This investigation has three parts. In the first part, students are introduced to levers as devices that help lift weight and overcome resistance. Also, they learn how to use spring scales. In the second part, students conduct an experiment by using a pre-built lever system to see how a lever can be advantageous. In this experiment, students keep the load stationary and change the position of effort. They collect data and represent them in a graph. Figure 16 displays an example of a sheet on which students record data and
represent them in a graph. In the third part, students conduct another experiment by using the same lever system. In this experiment, students apply the effort force to a fixed location on the lever arm and move the load to different positions. They record data and represent them on a graph sheet. At the end of investigation 1, there are three science stories for students. The titles of the stories include *Simple Machines, Class-1 Levers* and *The Wheel and Axle*.

*Figure 16. The worksheet on which students record data and represent them in a graph.*
**Investigation 2: More Leverage.** The aim of this investigation is that students will
(a) learn to identify class-1, class-2, and class-3 levers, (b) diagram levers to show
placement and direction of the load and effort, (c) analyze common tools in terms of
levers, (d) analyze pictures of tools in terms of levers, and (e) use scientific thinking
processes to conduct investigations and build explanations: observing, communicating,
comparing, organizing, and relating. The related science concepts that the investigation
aims to teach students include: a class-1 lever has the fulcrum between the load and the
effort; a class-2 lever has the load between the effort and fulcrum; a class-3 lever has the
effort between the fulcrum and the load; conventions are operating procedures that help
people communicate more efficiently; and advantage is a gain in effort, distance, or
change of direction resulting from the use of a simple machine.

This investigation has four parts. In the first part, students explore different
arrangements of lever arm, fulcrum, load and effort on lever systems. They learn which
arrangements are called class-1, class-2, or class-3 levers. In the second part, students
explore each class of lever systems. They learn how to diagram each class of levers by
diagramming different arrangements on the lever arm. In part three, students investigate
common real life tools such as broom, hammer, bottle opener, etc. to determine which
class of lever they belong to. Students are provided the *Levers at Work* sheet for
investigating common real life levers (Figure 17). On this sheet, students are provided
only with the names of real-life tools and are asked to determine what class of lever they
represent. In the fourth part, students analyze pictures of real-life tools such as a
wheelbarrow, a teeter-totter, a fishing rod, etc., identify them by their lever class and
draw their diagrams. At the end of investigation 2, there are three science stories provided for students. The titles of the stories include *Class-2 Levers*, *Class-2 Levers*, and *The Inclined Plane*.

*Figure 17.* The Levers at work sheet for investigating common real life levers.

**Investigation 3: Pulleys.** The aim of this investigation is that students will (a) assemble and investigate one- and two-pulley systems; (b) learn vocabulary associated
with pulley systems; (c) discover the advantages of using pulleys: decrease in effort and change in direction of effort; (d) diagram pulley systems; and (e) use scientific thinking processes to conduct investigations and build explanations: observing, communicating, comparing, organizing, and relating. The related science concepts that the investigation aims to teach students include: a single-pulley system can be set up in two ways, fixed or movable, a single-moveable-pulley system provides a mechanical advantage for its user, a single-fixed-pulley system provides no mechanical advantage, but changes the direction of the effort; two-pulley systems can be made with one fixed pulley and one moveable pulley; a two-pulley system in which the effort is applied upward provides a greater advantage than one in which the effort is applied downward.

This investigation has three parts. In the first part, students investigate one-pulley systems to lift a load: a fixed pulley and a moveable pulley. Students used spring scales to determine the effort needed in each system and to compare them. In the second part, students explore two-pulley systems and learn how a fixed pulley and a moveable pulley can be used together. In addition, students diagram four different pulley systems including either one or two pulleys. In the third part, students play a pulley game to practice their learning on pulleys. The game requires each group to build a pulley system from among the four pulley systems that they diagramed in the previous activity in 3 minutes. At the end of investigation 3, there are three science stories provided for students. The titles of the stories include Pulleys, Dear Boss and The Wedge.

**Investigation 4: Pulleys at Work.** The aim of this investigation is that students will (a) investigate pulley systems with one and two pulleys; (b) discover the relationship
between the number of ropes pulling on a load and the effort required to lift that load; (c) record and compare the distance between the number moved by the load and the effort in four different pulley systems; and (d) use scientific thinking processes to conduct investigations and build explanations: observing, communicating, comparing, organizing, and relating. The related science concepts that the investigation aims to teach students include: the effort needed to lift a load with a pulley system can be predicted; and the amount of work put into a system is equal to the work output of the system.

This investigation consists of three parts. In the first part, students explore four different pulley systems. They record the weight of the load, the effort needed to lift it and the number of ropes supporting the load. In the second part, students explore the relationship between distance, load, and effort to move an object by using a pulley system and creating mechanical advantage. Students lift a load 5 centimeters with four different pulley systems and record the distance over which the effort must be applied for each one. Through this activity, students learn that when the effort is reduced, the distance it must cover increases. In the third part, students choose a topic to investigate about lever and pulley systems. They try to design other lever and pulley systems. At the end of investigation 4, there are three science stories provided for students. The titles of the stories include The Work of Pulleys, The Screw and Thank you Mr. Clumpet.
Comparison of the Experimental and the Control Curriculum Units

The objectives for the *Design a People Mover: Simple Machines* in comparison to the inquiry-based FOSS unit are given in Table 3. The engineering-design unit includes six science content knowledge objectives and one engineering-design process objective with sub-items, while the inquiry-based unit includes ten content goals and seven science-as-inquiry goals. Generally, both of the curricular units want students to learn science content. However, the design-based LEGO™ curriculum also wants students to learn design context, whereas the inquiry-based curriculum wants students to learn inquiry process. In the design-based curricular unit, the learning goals consisted of separate content goals and engineering-design goals. In contrast, in the inquiry-based curricular unit, the inquiry process is embedded in the content goals and stated separately as well.

Table 3

*Learning objectives for the FOSS Levers and Pulleys Unit and for the Design a People Mover: Simple Machines Unit*

<table>
<thead>
<tr>
<th>FOSS Learning Goals</th>
<th>TESLED Learning Standards for <em>Design a People Mover: Simple Machines Unit</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>Goals</td>
<td>By the end of this module, students will be able to:</td>
</tr>
<tr>
<td>1)</td>
<td>1) Explain what the following simple machines do to help humans:</td>
</tr>
<tr>
<td></td>
<td>a) Levers, which are stiff bars that rotate around fixed points, make it easier to lift a load or apply a force.</td>
</tr>
<tr>
<td>2)</td>
<td>b) Wheel-and-axles, which are two differently-sized wheels attached to the same axis, are used to make circular motion easier.</td>
</tr>
<tr>
<td>3)</td>
<td></td>
</tr>
</tbody>
</table>

1) Gain experience with the concept of force and the application of force to do work
2) Gain experience with the relationship between the components of lever systems and pulley systems
3) Gain experience with the concept of advantage as it relates to simple machines
<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>4)</td>
<td>Analyze real-world tools and machines in terms of the simple machines that make them work.</td>
</tr>
<tr>
<td>5)</td>
<td>Systematically collect and record data.</td>
</tr>
<tr>
<td>6)</td>
<td>Use measurement in the context of scientific investigations.</td>
</tr>
<tr>
<td>7)</td>
<td>Use diagrams to translate three-dimensional relationships into two dimensions.</td>
</tr>
<tr>
<td>8)</td>
<td>Acquire vocabulary associated with two simple machines (levers and pulleys).</td>
</tr>
<tr>
<td>9)</td>
<td>Apply mathematics in the context of science.</td>
</tr>
<tr>
<td>10)</td>
<td>Use scientific thinking process to conduct investigations and build explanations: observing, communicating, comparing, organizing, and relating.</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>c)</td>
<td>Inclined planes, which are surfaces slanted upwards, lower the effort needed to lift a load.</td>
</tr>
<tr>
<td>d)</td>
<td>Wedges, which are two inclined planes joined back to back to form a sharp edge, are used to change the direction of a force and often result in the splitting of objects.</td>
</tr>
<tr>
<td>e)</td>
<td>Screws, which are inclined planes wrapped around a cylinder, are used to raise and lower objects and hold objects together.</td>
</tr>
<tr>
<td>f)</td>
<td>Pulleys, which are wheels with grooved edges for ropes, are used to change the direction of a pull and make it easier to lift a load.</td>
</tr>
<tr>
<td>g)</td>
<td>Gears, which are wheels with teeth around the edge, are used to turn other gears and change the direction, speed, and force of circular motion.</td>
</tr>
</tbody>
</table>

**More generally:**
Recognize that simple machines help humans by:
(a) decreasing the input force and increasing the input distance or (b) increasing the input force and decreasing the input distance needed to do work. Simple machines do not change the amount of work done

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2)</td>
<td>Identify examples of simple machines in everyday objects.</td>
</tr>
<tr>
<td>3)</td>
<td>Identify simple machines within complex machines.</td>
</tr>
<tr>
<td>4)</td>
<td>Choose appropriate simple machines to solve a mechanical problem.</td>
</tr>
<tr>
<td>5)</td>
<td>Define engineering design as the process of creating solutions to human problems through creativity and the application of math and science knowledge.</td>
</tr>
<tr>
<td>c)</td>
<td>List and explain the following steps of the engineering design process:</td>
</tr>
<tr>
<td></td>
<td>i. Identifying a problem</td>
</tr>
</tbody>
</table>
Kolodner, Gray, and Fasse’s (2003) model of the cycles of activities involved in learning from design activities (Figure 1 and 18) may serve as an excellent tool to define the different aspects of the two curricular units.


Kolodner et al. (2003) defined two parallel cycles of activities in design-based learning. The sequence of the design/redesign cycle includes messing around with materials and devices to understand the challenge, engaging in a problem-based learning to define what needs to be investigated, planning a design, constructing, testing, and analyzing the design. The sequence of the investigate and explore cycle includes clarifying the
question, generating a hypothesis about it, designing the investigation, conducting and analyzing it, and finally presenting and sharing it in a poster session.

The inquiry-based curriculum focuses on the “investigate and explore” cycle while the design-based unit focuses on the design/redesign cycle. Therefore, the seven science-as-inquiry goals were considered as the characteristic features of the inquiry-based curricular unit, while the fifth learning standard for the *Design a People Mover: Simple Machines Unit* were considered as the characteristic features of the engineering-design curricular unit.

**Research Design**

The research design of the study was a quasi-experimental design. The design of the research that I have conducted can be seen in Table 4. In this table, the control and the experimental groups, the treatment, and the measurements before and after the treatment are shown. The Control group was the fifth grade students from the [Walnut] Elementary school, whereas the experimental group was the fifth grade students from the [Peanut] Elementary School. $O_1$ represents the written test while $O_2$ represents the interview. $X_1$ represents teaching simple machines by an inquiry-based curriculum, (the *Pulleys and Levers* unit in FOSS), while $X_2$ represents the LEGO™ engineering-design unit on simple machines (See Table 3 for a comparison of learning objectives of the two units). As it can be seen in Table 3, identical written tests and identical interviews were used before and after the instruction.

Table 4.

*Summary of the research design*
<table>
<thead>
<tr>
<th>Group</th>
<th>Pre</th>
<th>Treatment</th>
<th>Post</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Group</td>
<td>$O_1 \ O_2$</td>
<td>$X_1$</td>
<td>$O_1 \ O_2$</td>
</tr>
<tr>
<td>Experimental Group</td>
<td>$O_1 \ O_2$</td>
<td>$X_2$</td>
<td>$O_1 \ O_2$</td>
</tr>
</tbody>
</table>

**Data Sources and Data Collection**

I collected data from multiple sources. I used a design-based LEGO™ curriculum unit on simple machines and an inquiry-based curriculum unit on simple machines. I administered pre and post written tests to measure students’ understanding of simple machines. The pre- and the post-test included 6 multiple choice and 5 open-ended questions, which are identical. Also, I administered pre and post interviews to explore students’ in-depth understanding of simple machines and their construction of simple machine concepts as well. I interviewed one third of the students in each classroom, and videotaped the interviews. The students for interviews were selected randomly among the students whose parents give me permission to videotape. I observed and videotaped a selection of lessons. I videotaped the lever and the pulley lessons of the both curricula, and the final design challenge lesson of the experimental curriculum. I chose these lessons because levers and pulleys are the common simple machines taught in the FOSS and TESLED units. Also, levers and pulleys are commonly used in students’ final designs in the experimental unit, so I wanted to observe how students learn these simple machines during the instruction and how they use them in their final design challenges.

Lastly, I collected students’ engineering journals from the experimental group and students’ workbooks from the control group. The engineering journals and student
workbooks include students’ reflections on the exploration questions, drawings, and writings in each lesson. The engineering journals and the student workbooks were subsidiary to the main data sources. Students’ drawings, writings and answers to exploration questions helped me understand how the inquiry curriculum or the LEGO™ engineering curriculum helped students build, refine or restructure their conceptual understanding of science concepts regarding simple machines.

**Data Collection Tools and Their Development**

All the researchers in the larger study collaboratively developed the written test addressing science and engineering learning objectives for the simple machines module. These items were developed in such a way that they can be used across comparisons and across classrooms. Then these assessment items were tested and modified based on student and teacher feedback. This written test was used to examine students’ science conceptions and learning in both the experimental and control classrooms.

The assessment instruments were developed based on Sternberg’s triarchic teaching and assessment methods (Grigorenko, Jarvin, & Sternberg, 2002). In order to address all learning types, creative, practical, analytical, and memory assessment questions were written for the simple machines units based on the unit objectives. Questions were ranked and edited by several researchers. Teacher feedback on the difficulty level of questions was also obtained from pilot teachers. Several researchers including science educators, engineers, engineering educators, and psychologists independently reviewed the questions and rated their (a) difficulty level, (b) cognitive skill type addressed (memory, analytical, practical or creative), and (c) relevant
objective(s). Questions on which consensus could not be reached were eliminated or further edited until consensus was reached. A chart of all the objectives and learning types was created to ensure that each objective was addressed with questions targeting different learning types. Table 5 shows the cognitive skill that each written-test item measures and the objective that each item addresses. With the written test, all of Sternberg’s (Grigorenko, et al., 2002; Sternberg et al., 2001) cognitive skills -memory, analytic, practical and creative- are being tested. Likewise, all of the objectives of the curricular unit are being addressed with the written-test items as well. Questions were added to make sure both of these conditions were met.

Table 5

*The cognitive skills that the written-test items measure and the objectives that they address*

<table>
<thead>
<tr>
<th>Item number</th>
<th>Format</th>
<th>Cognitive skill</th>
<th>Science objective</th>
<th>Rating scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (quarter vs. screwdriver)</td>
<td>OE</td>
<td>Practical</td>
<td>1a</td>
<td>0-2</td>
</tr>
<tr>
<td>2 (Twiggy &amp; Sticky)</td>
<td>MC</td>
<td>Analytic</td>
<td>1c</td>
<td>0-1</td>
</tr>
<tr>
<td>3 (simple machine example)</td>
<td>OE</td>
<td>Practical</td>
<td>2</td>
<td>0-2</td>
</tr>
<tr>
<td>4 (simple machine for pulling)</td>
<td>OE</td>
<td>Practical</td>
<td>4</td>
<td>0-2</td>
</tr>
<tr>
<td>5 (wheel &amp; axle pictures)</td>
<td>OE/MC</td>
<td>Analytic</td>
<td>1b</td>
<td>0-1</td>
</tr>
<tr>
<td>6 (knife)</td>
<td>MC</td>
<td>Analytic</td>
<td>1d</td>
<td>0-1</td>
</tr>
<tr>
<td>8 (gear picture)</td>
<td>MC</td>
<td>Analytic</td>
<td>1g</td>
<td>0-1</td>
</tr>
<tr>
<td>9 (screw pictures)</td>
<td>MC</td>
<td>Analytic</td>
<td>1e</td>
<td>0-1</td>
</tr>
</tbody>
</table>
The *Design a People Mover: Simple Machines* unit has eleven objectives. For each objective, one question was selected. The aim was to create assessments with questions that addressed every learning objective and approximately equally represented all of the learning types. The pre- and post-written tests for the unit were identical, and they included both multiple-choice and open-ended questions. The written test on simple machines included eleven questions, with six open-ended and five multiple-choice questions. One of the open-ended questions only required brief word or fill-the-blank answers. One multiple choice question asked students to circle all answers that apply to the question. The written test on simple machines is given in Appendix D.

To get a deeper understanding of what students know about simple machines and how they construct their knowledge and make sense of simple machine concepts, an interview protocol was developed by my advisor and me. With piloting of the interview protocol and consultations received from the other researchers working on the project, the interview protocol was developed over the course of two years. The interview protocol, which is given in Appendix E, includes five main questions and their sub-questions. The second written test item and the third interview item concern the same phenomena; however, in the interview item, students are asked to explain their answer in more detail.
Study Context

The Experimental School and the Experimental Teacher. During the 2009-2010 academic year, the [Peanut] Elementary School, which is a Boston Public School (BPS), participated in the study as the experimental school. A fifth grade teacher implemented the LEGO™ engineering-design based curriculum unit. The two fifth grade classrooms in this school participated as experimental classrooms. During the year in which this study was conducted, the school had the following demographics: 65.9% Hispanic, 29.8% African American, 2.3% White, 0.8% Asian, and 1.8% Multi Race, Non-Hispanic. Also the school had 47.9% Regular Education, 22.3% Special Education, and 29.7% Bilingual Education students. 43% of the fourth graders from the [Peanut] Elementary School last year scored proficient or above in MCAS English Language Arts section whereas 44% scored proficient or above in MCAS Math section.

The LEGO™-based, engineering-oriented Design a People Mover: Simple Machines unit, which was developed for fourth and fifth grades by our research team, was used as an instrument. The unit includes eleven lessons, and each lesson is prepared for a 60-minute period. One of the two fifth grade teachers taught the science and technology unit to both of the classes in the experimental school. Students were enrolled in each class with 10 boys and 7 girls in each.

The experimental teacher was female with fourteen years of teaching experience. She has a Hispanic background, and her first language is Spanish. She holds a BA degree in Mathematics and Physics and a Master’s degree in Bilingual Teaching. She had been teaching science for ten years and fifth grade for eleven years. She rated her comfort level
when teaching science lessons 2 (moderately comfortable) from within a scale ranging from 1- very comfortable to 5-very uncomfortable.

The experimental teacher taught three lessons a week, so the implementation of the unit took five weeks. There are two fifth grade classrooms in the school. I observed and videotaped the levers, pulleys and the final design lessons. The pre-test and the pre-interviews had been conducted before the instruction, and the post test and the post interviews had been conducted within two weeks after the unit’s completion.

**The Control School and the Control Teacher.** The control school, the [Walnut] Elementary School is within the BPS system as well. One of the two science teachers who is also the science specialist of the school taught the simple machines unit via the regular science curriculum that the BPS uses (FOSS *Levers and Pulleys* unit) with a few extracurricular activities of his own. The two fifth grade classrooms in this school participated as control classrooms. During the year in which this study was conducted, the school had the following demographics: 61.3% Hispanic, 12.5% African American, 12.5% Asian, 11.3%, White, and 1.8% Multi Race, Non-Hispanic. 44% of the fourth graders from the [Walnut] Elementary School last year scored proficient or above in MCAS English Language Arts section whereas 25% scored proficient or above in MCAS Math section.

The control teacher was a male teacher with six years of teaching experience. He holds a BA degree in business and a Master’s degree in elementary education. He had been teaching science for six years and fifth grade for six years. He rated his comfort level when teaching science lessons 1 (very comfortable) from within a scale ranging
from 1- ‘very comfortable’ to 5-‘very uncomfortable’. He is working as a science specialist in the school and also as a science teacher trainer.

The control teacher taught three lessons a week, so the implementation of the unit took approximately five weeks; however with interruptions such as holidays, field trips and the Massachusetts Comprehensive Assessment System (MCAS) exams, the total time to finish the unit took approximately seven weeks. There are two fifth grade classrooms in the school. I observed and videotaped one lesson on levers and two lessons on pulleys. The pre-test and the pre-interviews had been conducted before the instruction, and the post test and the post interviews had been conducted within two weeks after the instruction.

**Data Analysis**

To analyze students’ responses for the written tests and for the interview questions, answer keys for multiple choice questions and rubrics for the open-response and interview questions were created. The rubric for the written test is given in Appendix F, and the rubric for the interview questions is given in Appendix G. Students’ answers to questions were scored according to these rubrics.

For each multiple choice question students get a score from 0 to 1. In questions 2, 6, 8, and 9, students get 0 when they choose a wrong answer and 1 when they choose a correct answer. In question 5, students get 0.25 for circling the door knob, the handlebar, the Jack-in-the-Box handle, and not circling the CD.

For the open-ended questions, students’ can get 0, 1 or 2 points for their answers. Students get 0 if they give a totally wrong answer, no answer, or an irrelevant answer. In
question 1, students get 1 if they only discuss the merits of a screwdriver or a quarter in a way that is not fully accurate, but have elements of the force-distance trade-off; and get 2 if they discuss leverage or the force-distance trade-off involved in using the lever or the quarter. In question 3 and 7, students get 1 if they give a correct answer for only one of the two parts of the question, and they get 2 if they give a correct answer for both parts of the question. In question 4, students who list a pulley, inclined plane, wheel and axle, or gear as the simple machine that helps lift heavy things get 1, and students who provide an explanation that uses the simple machine listed to pull a heavy object get 2. In question 10, students whose drawings include a pulley, which is not labeled or is labeled incorrectly, get 1. Students whose drawings include a pulley in a way that it would be used and is currently labeled get 2. In question 11, students get 0.5 for each simple machine that they label correctly up to 4 simple machines.

For the interview questions, students’ can get 0, 1, 2, or 3 points for their answers. Students get 0 if they give a totally wrong answer, no answer, or an irrelevant answer. Students get 1 if their answer reflects a confused, incomplete, or inaccurate understanding of the phenomena. They get 2 if their answer reflects a partial understanding of the phenomena. They get 3 if their answer reflects a complete understanding of the phenomena.

Students participated in two types of assessments. The written assessment consisted of multiple-choice (MC) and open-ended (OE) items that were scored by using the rubric given in Appendix F. The content interviews consisted of semi-structured questions and their follow ups that were scored by using the rubric given in Appendix G.
The content interviews were given to a subset (approximately one third) of the students. One third of participants’ open-ended items on the written tests and the interview items were scored by two science educators. The agreement percentages on the open-ended and interview items are given in Table 6. The means for the agreement percentages for both the open-ended and the interview items were 85.2 %. Thus, one of the science educators continued to score all the items and his scores were used in the statistical analyses.

Table 6

**Inter-rater scoring agreement percentages for the open-ended test items and for the interview items**

<table>
<thead>
<tr>
<th>Open-ended Items</th>
<th>Percent Agreement</th>
<th>Interview Items</th>
<th>Percent Agreement</th>
</tr>
</thead>
<tbody>
<tr>
<td>OE Item 1</td>
<td>85.71 %</td>
<td>Item 1</td>
<td>83.33 %</td>
</tr>
<tr>
<td>OE Item 3</td>
<td>88.88 %</td>
<td>Item 2</td>
<td>79.17 %</td>
</tr>
<tr>
<td>OE Item 4</td>
<td>88.88 %</td>
<td>Item 3</td>
<td>86.36 %</td>
</tr>
<tr>
<td>OE Item 7</td>
<td>82.54 %</td>
<td>Item 4</td>
<td>90.91 %</td>
</tr>
<tr>
<td>OE Item 10</td>
<td>85.71 %</td>
<td>Item 5</td>
<td>86.36 %</td>
</tr>
<tr>
<td>OE Item 11</td>
<td>79.36 %</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7 shows the areas of investigation, the data sources to be used, and the analyses that were made to answer the questions. I used an interpretive framework (Denzin and Lincoln (2008) to analyze my data. To investigate the impact of an engineering design-based simple machines curriculum compared to a scientific inquiry-
based simple machines curriculum (FOSS) on student learning outcomes, I compared the control and the experimental groups’ scoring on the tests and the interviews. I ran an Analysis of Covariance (ANCOVA) test and held the pre-scores constant (they become a covariant) on SPSS software. To investigate what kids learn in each of the two curriculum areas, I compared students’ scores for each item in the written tests and in the interviews before and after the instruction by running match analysis on Microsoft Excel.

Table 7
Areas of investigation, data sources to be used and the analysis that were made to answer the questions

<table>
<thead>
<tr>
<th>Areas of Investigation</th>
<th>Data Sources</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>What do the students learn in regards to the science of simple machines in a LEGO-engineering design unit and a scientific inquiry-based unit?</td>
<td>Written Tests, Interviews</td>
<td>Pre MC - Post MC → Paired t-test&lt;br&gt;Pre OE - Post OE → Paired t-test&lt;br&gt;Pre-Int - Post Int → Paired t-test&lt;br&gt;Match Analysis</td>
</tr>
<tr>
<td>How do the curricular characteristics support students in learn science content and support students in changing their misconceptions?</td>
<td>Written Tests, Interviews, Video-tapes (Observation)</td>
<td>PostMCCont – PostMCExp → ANCOVA&lt;br&gt;PostOECont - PostOEExp → ANCOVA&lt;br&gt;PostIntCont - PostIntExp → ANCOVA&lt;br&gt;Effect Sizes</td>
</tr>
</tbody>
</table>
To investigate how both the curricula helped students learn science content and overcome their science misconceptions, I analyzed observation videotapes and student workbooks as a subsidiary data source. To analyze the classroom observation videotapes, I used Jordan and Henderson (1995)’s method and divided the videos into episodes. When the topic or idea or something shifts or changes in the video, then that was considered as an end of a section and a beginning of another section. Therefore usually these video episodes can range anywhere from a couple of minutes to half an hour. These video episodes were then grouped and analyzed holistically with the goal of identifying particular features or characteristics of curricula that help students learn content and overcome their misconceptions.

I analyzed observation videotapes and student workbooks to investigate how the curricula were implemented by the experimental and the control teachers and the advantageous and disadvantageous features of both the curricula as subsidiary data sources. I explored how the teachers modify the curricular unit they implemented and what features of the curriculum they emphasized during implementation. I did not transcribe or focus on every video episode because not all of the video episodes were relevant to my areas of investigation. When the teacher was talking to the whole class and leading a class discussion, I videotaped the whole class (except the students whose parents do not give consent to being videotaped) and the teacher. On the other hand, while students were working in groups, I focused on a group of students. I picked that group randomly among the students whom I was allowed to videotape.
Summary of Methods

In this dissertation study I used a mixed methodological approach in order to investigate how LEGO™ engineering-design curriculum materials may improve students’ content understanding and help them establish their conceptual frame for the content. The research design was a quasi-experimental design. Identical written tests and interviews were conducted before and after instruction to both the experimental and the control groups. The fifth grade students from the [Walnut] Elementary school participated as the control group while the fifth grade students from the [Peanut] Elementary School are participating as the experimental group.

I used the LEGO™-based and engineering oriented Design a People Mover: Simple Machines unit and the inquiry based Levers and Pulleys unit as instruments. Design a People Mover: Simple Machines unit is developed by a team of Boston College and Tufts University researchers and has undergone a rigorous testing for the last two years. Levers and Pulleys unit is a unit in the Full Option Science System (FOSS) curriculum, which is currently in use in many school districts including the Boston public schools.

I collected data from multiple sources. Data from content tests, student interviews, classroom observations, engineer’s journals, and student workbooks informed me as to learn how LEGO™ engineering-design curricular module on simple machines in comparison to the inquiry-based curricular module on simple machines affects students’ learning of simple machines. Furthermore data from multiple sources allowed me to examine what kids learn in each of the two curriculum areas, how they help them learn
science content and overcome their science misconceptions, and what the advantageous and disadvantageous features/characteristics of both curricula are.

To analyze the written tests and the interviews, I used rubrics. The rubrics as well as the written test the interview protocols had been developed over the course of two to three years by a collaboration of a team of researchers, so they actually had gone through fairly rigorous testing. Several researchers evaluated the items as they had been piloted in the classrooms.
CHAPTER 4. FINDINGS

In this chapter, I present analyses of both the quantitative and the qualitative data collected in this study. The data are analyzed and presented in four sections. In the first section, the curricular units used in the control school and the experimental school are analyzed. Included in this section are the objectives of the units, the instructional tools of the units, and teachers’ implementation techniques of the curricula. In the second section, the multiple-choice items of the written assessments, pre- and post-, are analyzed. Comparisons among groups in post-multiple-choice scores while controlling for pre–multiple-choice score differences are presented. Additionally, analysis of the multiple-choice items based on Sternberg’s triarchic assessment approach is presented. In the third section, the open-ended items of the written assessments, pre- and post-, are analyzed. Comparisons among groups in post-open-ended scores while controlling for pre–open-ended score differences are presented. Additionally, analysis of open-ended items based on Sternberg’s triarchic assessment approach is presented. In the fourth section, the content interview assessments, pre- and post-, are analyzed. Additionally, comparisons among groups in post-interview scores while controlling for pre–interview score differences are presented. In the final section, a summary of the findings is presented.

Curriculum Implementation

In this section, I present case studies of how the control teacher and the experimental teacher implemented the simple machines curricula they used. For each teacher, I begin by describing how they personalized the curricular units and the
instructional tools they used. Next, I compare each teacher’s implementation of the curricular units in terms of their instructional decisions and abilities.

**Daniel’s Implementation of the FOSS Levers and Pulleys Curriculum.** Based on classroom observations and communications with Daniel during the enactment of the curriculum, I portray his curriculum design and implementation in two sections to further characterize how he enacted the FOSS Levers and Pulleys curriculum. In the first section, I describe how Daniel personalized the curriculum by adding to or extracting parts from the curriculum. In the second section, I describe how he implemented the curriculum.

**Daniel’s Personalization of the Curriculum.** Daniel's curriculum use was characterized by his prior experiences of teaching the unit and updating and redesigning his instructional materials to enact them this year. I observed that Daniel mainly used the FOSS teacher’s guide as his reference in designing his instruction. This process included revisiting the teacher’s materials of the unit and his instructional materials from previous years and designing instruction prior to his enactment. This process was followed by multiple cycles of reading and evaluating the teacher’s guide and his own instructional materials. His instructional materials consisted of PowerPoint slides that included lesson objectives and questions, pictures, graphs and vocabulary. Since Daniel has been teaching the FOSS Levers and Pulleys unit for several years, there were no major novelties in his enactment during the year in which this study was conducted. One of the most significant changes was that he did not have an exploratory lesson in which he used to go out to the school yard with his students to explore simple machines around the schoolyard. During his enactment he was holding this lesson as an option at the end of the unit; however, he
did not have time to do it. Instead of this exploratory lesson, Daniel showed students BrainPop\textsuperscript{2} short clips about simple machines. BrainPop uses animated characters, voice, diagrams and simulations to explain scientific phenomena. Daniel showed his students five clips about levers, pulleys, inclined planes, wheel and axles, and gears.

**Daniel’s Instruction of the Curriculum.** Daniel prepared the classroom for students in advance. He set up lever systems on each table that groups of students used. He posted related posters on the walls of the classroom. These posters included vocabulary, figures, graphs and pictures related to the lessons. Also he placed a display shelf for books next to the entrance. On the display shelf, there were all sorts of books related to simple machines. He prepared the lesson overviews, objectives and poster pre-prepared as Microsoft PowerPoint slides. During the implementation, Daniel often used a laptop computer and a projector to project those PowerPoint slides as well as educative video clips about simple machines on the screen.

The layout for Daniel’s classroom is displayed in Figure 19. Because Daniel teaches science to third, fourth, and fifth graders in this classroom, there were other posters that are for third and fourth graders on the side walls. Daniel arranges students’ desks differently for different grades. This classroom layout allows the students to see each others’ faces during the instruction. Also, most of the time, Daniel was able to see the faces of all the students. Furthermore, this classroom layout helped Daniel to manage the classroom more easily. While students were doing the activities, he was easily able to

\textsuperscript{2} [http://www.brainpop.com/](http://www.brainpop.com/)
visit different groups. Also, when he wanted to show an exemplary activity of one group to the other groups, all the students from other groups could see it without difficulty.

Daniel developed a warning system for managing the classroom. He always had a class list ready with him. When a student was not behaving, he first warned him or her verbally. If he or she continued to misbehave, then he gave him or her a warning and recorded it on the class list. At the end of the class, Daniel gave this warning list to their classroom teacher.

*Figure 19.* The classroom layout for Daniel’s classroom.
Another method that Daniel used to refocus his students involved ringing a bell. When students were off the topic and there was too much noise around, he rang the bell and all the students stopped moving or making noise. Then Daniel redirected students to their work.

Also, to reduce preparation time and increase the instructional time, he previously determined the “getter” of each group to get materials for each activity for their groups. Therefore, just one student from each group got materials for activities rather than having all students involved in getting materials.

**Maria’s Implementation of the Design a People Mover: Simple Machines**

Curriculum. Based on classroom observations and communications with Maria during the enactment of the curriculum, I portray her curriculum design and implementation in two sections to further characterize how she enacted the Design a People Mover: Simple Machines curriculum. In the first section, I describe how Maria personalized the curriculum by implementing it. In the second section, I describe how she implemented the curriculum.

**Maria’s Personalization of the Curriculum.** Maria teaches science and mathematics to fifth grade classes in the school. She had taught the Design a People Mover: Simple Machines unit for two years. Last year she taught the unit to two fifth grade classes for the first time. This year she again taught the unit for the two fifth grade classes in the school. She used to teach simple machines by using the FOSS Levers and Pulleys unit. Maria had four years of prior experience teaching the FOSS unit; however, this was her second time enacting a design-based unit. During the summer of 2008, Maria
attended a workshop for teaching design-based units. This workshop was designed specifically for teachers in Maria’s school to introduce them to four design-based units that were developed by Boston College and Tufts University researchers and to teach them how to teach those units.

Maria was one of the twelve teachers who attended the workshop. The workshop took four days from 9 am to 3 pm with half an hour lunch break at noon. In each day, developers of the design-based units explained how to teach one of the units. Before Maria started teaching the unit during the school year, I had a meeting with Maria. We reviewed the lesson plans together and she had a chance to ask questions or discuss characteristics of the unit with me. We had a similar meeting before she taught the unit this year as well, but for a shorter time -only about an hour-. Maria’s curriculum use was characterized by the workshop she attended, the meetings with me and the Design a People Mover: Simple Machines unit teacher’s guide provided within the unit kit. She mainly used the unit teacher’s guide as her reference in designing her instruction. This process included revisiting the teacher’s materials of the unit and designing instruction prior to her enactment. This process was followed by multiple cycles of reading and evaluating the teacher’s guide.

Maria did not add or extract parts from the unit. She focused on the teacher’s guide and tried to follow the guide strictly. Since using design-based instruction as a method to teach science was new for her, Maria was not so comfortable with teaching the design-based unit. When I was present in the classroom for observing the class, she explicitly asked me about what she should do next and directed some of students’
questions to me. I tried to answer any questions relating to the technical background of the unit, such as the use of Lego™ pieces, or some details about the pieces, such as how many teeth a gear has on it. However, I made clear that any decisions regarding the instruction should be made by her.

**Maria’s Instruction of the Curriculum.** Maria did not make any physical changes in the classroom before the instruction. Since she teaches both mathematics and science to the fifth graders, she made a shift from science to math or vice versa. During these shifts she often gave a snack break or a bathroom break for a couple of minutes. Maria did not often use posters relating to simple machines. She only used a couple posters that I gave to her. Also, she used the white board very few times for instructional purposes. She often used the white board to write assignments for the next class. On the other hand, she used the easel pad very often. She wrote vocabulary words for each lesson and drew diagrams of simple machines on the easel pad. Maria had a laptop computer and a projector and a smart board system available in the classroom. However, Maria used the smart board only a few times for projecting Engineer’s Journals on the screen during the implementation.

The layout for Maria’s classroom is displayed in Figure 20. Maria designed the classroom in such a way that not all the students could see each others’ faces and she had little space for walking around the classroom. She sometimes had difficulty keeping her students’ attention on the subject. Accordingly, she complained about falling short of time. Students’ seating design and the classroom design allowed for distractions and made managing the classroom difficult for her. Especially the students sitting inside the
“U” shaped desks were open to being distracted by other students as well as distracting them. Another source for distraction was the back door, which exits to the other fifth grade classroom. Students from the next classroom frequently stepped in to Maria’s classroom to pick up their belongings, such as a pencil or a backpack that they left during their previous science or math class. Since Maria did not have any arrangement for getting the Lego™ materials for design activities, almost every student wanted to get them and some chaos taking a few minutes out from instructional time was inevitable.
**Comparison of the Experimental and the Control Curriculum Units.** The objectives for the Design a People Mover: Simple Machines unit in comparison to the inquiry-based FOSS unit are given in Chapter 3. The engineering-design unit includes six science content knowledge objectives and one engineering-design process objective with sub-items, while the inquiry-based unit includes ten content goals and seven science-as-inquiry goals. Generally, both of the curricular units aim for students to learn science
content. However, the design-based LEGO™ curriculum also aims for students to learn about the design context, whereas the inquiry-based curriculum aims for students to learn about the inquiry process. In the design-based curricular unit, the learning goals consisted of separate content goals and engineering-design goals. In contrast, in the inquiry-based curricular unit, the inquiry process is embedded in the content goals and is stated separately as well.

Figure 21 shows the shared and different objectives of both curricula. I prepared this figure based on the objectives each curriculum listed in their modules. I found that most of the content related objectives are common for both the units. Both the design-based unit and the inquiry-based unit cover gears, screws, levers, pulleys, inclined planes, wheel and axles, and force and its applications to do work as content, while complex machines are covered only by the design-based unit. In terms of procedural objectives, both the units aim to teach analyzing alternative explanations and solutions, employing tools to gather, analyze, and interpret data, analyzing real-world tools, and using diagrams and mathematics to make explanations.

The inquiry-based curriculum involves identifying questions for investigations while the design-based curriculum involves identifying a problem to solve. Researching possible solutions, picking the best solution, building and testing a prototype, and repeating any steps needed to improve the design are endemic to the design-based curriculum.

Using evidence to make reasonable explanations and understanding scientific investigations were explicitly stated in the inquiry-based curriculum as its objectives. One
can argue that students are encouraged in the design-based curriculum to use evidence for making reasonable explanations and to make meaning of scientific investigations. For example, during the whole-class discussions in the design-based curriculum, students are encouraged to share and explain their ideas with other students by using evidence. In addition, one of the major differences between the two curricula are that in the inquiry-based curriculum, students collect data by using pre-built experimental set ups, whereas in the design-based curriculum students first design the experimental set-up and then collect data. Another major difference between the two curricula is that students working on a design challenge know why they are designing because they are working on a real-life problem. In contrast, students working on an inquiry activity often lack that knowledge. Students doing inquiry may say that they are doing the inquiry to answer the investigation questions; however, to investigate and design for solving a real-life problem is more realistic to students.
Figure 21. Shared and different objectives of the inquiry-based and the design-based curricula.

The FOSS Levers and Pulleys unit focuses primarily on teaching levers and pulleys and aims to teach other simple machines by short stories about them. To address this deficiency, the control teacher, Daniel, showed his students short clips about the other simple machines. In addition, based on the collaboration between Daniel and classroom teachers, the short stories were read during English classes. In contrast, the Design a People Mover: Simple Machines unit aims for teaching wheels and axles, gears, screws, inclined planes, and wedges as well as levers and pulleys. Both of the curricular units are designed for twelve hours of instructional time. It took fourteen hours for Daniel
to finish the unit while Maria finished the unit in sixteen hours. The content Daniel covered and the time he spent for teaching the content of each lesson are shown in Table 8. Daniel did not cover the last lesson because he ran out of time. The content Maria covered and the time she spent for teaching the content of each lesson are shown in Table 9. Each of the design-based lessons were expected to take an hour of instruction time; however, the lessons that required design of simple machines took more time than expected for Maria to teach.

Table 8

*The content Daniel covered and the time he spent for teaching the content of each lesson*

<table>
<thead>
<tr>
<th>Content</th>
<th>Teacher: Daniel</th>
</tr>
</thead>
<tbody>
<tr>
<td>how to use spring scales</td>
<td>1 hour</td>
</tr>
<tr>
<td>experiment with a pre-built lever system: keep the load stationary and change the position of effort</td>
<td>2 hours</td>
</tr>
<tr>
<td>experiment with a pre-built lever system: keep the position of effort stationary and change the position of load</td>
<td>1 hour</td>
</tr>
<tr>
<td>class-1, class-2, or class-3 levers</td>
<td>2 hour</td>
</tr>
<tr>
<td>how to diagram each class of levers</td>
<td>1 hour</td>
</tr>
<tr>
<td>to investigate common real life tools</td>
<td>1 hour</td>
</tr>
<tr>
<td>to analyze pictures of real-life tools</td>
<td>1 hour</td>
</tr>
<tr>
<td>one-pulley systems: a fixed pulley and a moveable pulley</td>
<td>1 hour</td>
</tr>
<tr>
<td>two-pulley systems</td>
<td>1 hour</td>
</tr>
<tr>
<td>play a pulley game</td>
<td>1 hour</td>
</tr>
<tr>
<td>to explore the relationship between distance, load, and effort</td>
<td>2 hour</td>
</tr>
<tr>
<td>to design other lever and pulley systems</td>
<td>No time</td>
</tr>
</tbody>
</table>
Table 9

*The content Maria covered and the time she spent for teaching the content of each lesson*

<table>
<thead>
<tr>
<th>Content</th>
<th>Time Spent</th>
</tr>
</thead>
<tbody>
<tr>
<td>introduction to the final design challenge</td>
<td>1 hour</td>
</tr>
<tr>
<td>to explore examples of the seven different simple machines</td>
<td>2 hours</td>
</tr>
<tr>
<td>mechanics of levers and the ways levers can help humans</td>
<td>1 hour</td>
</tr>
<tr>
<td>the mechanics of two-armed levers and the ways they can help humans to identify everyday examples of levers</td>
<td>2 hours</td>
</tr>
<tr>
<td>to test wheel-and-axle systems of different shapes and sizes to determine which requires the least effort to turn a model food mixer.</td>
<td>2 hours</td>
</tr>
<tr>
<td>the uses of inclined planes, screws, and wedges and the ways they can help humans</td>
<td>1 hour</td>
</tr>
<tr>
<td>to explore differently sized pulleys and observe the force and distance of pull with fixed and moveable pulley systems</td>
<td>2 hours</td>
</tr>
<tr>
<td>the uses of gears and the ways gears can help humans to change the direction, speed, and force of circular motion</td>
<td>1 hour</td>
</tr>
<tr>
<td>to analyze complex machines to identify the simple machines within them</td>
<td>1 hour</td>
</tr>
<tr>
<td>to construct, review, modify, and diagram their model people movers</td>
<td>2 hours</td>
</tr>
<tr>
<td>to share their complex machines with other students</td>
<td>1 hour</td>
</tr>
</tbody>
</table>

**Comparisons between the Control and the Experimental Teachers.** Table 10 provides a summary of the teachers’ demographics, background and teaching experience. More details will be given below.
Table 10

*Teacher demographics, background and experience*

<table>
<thead>
<tr>
<th>Category</th>
<th>Daniel</th>
<th>Maria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>mid 30s</td>
<td>50s</td>
</tr>
<tr>
<td>Gender</td>
<td>Male</td>
<td>Female</td>
</tr>
<tr>
<td>Race/Ethnicity</td>
<td>Caucasian</td>
<td>Hispanic</td>
</tr>
<tr>
<td>Grade Level</td>
<td>3&lt;sup&gt;rd&lt;/sup&gt;-5&lt;sup&gt;th&lt;/sup&gt; grade</td>
<td>5&lt;sup&gt;th&lt;/sup&gt; grade</td>
</tr>
<tr>
<td>Years Teaching</td>
<td>6</td>
<td>14</td>
</tr>
<tr>
<td>Subject/s Teaching</td>
<td>Science</td>
<td>Science, mathematics, Spanish</td>
</tr>
<tr>
<td>Undergraduate Major</td>
<td>Business</td>
<td>Math and Physics</td>
</tr>
<tr>
<td>Graduate Degree</td>
<td>Masters in Elementary Education</td>
<td>Masters in Bilingual Education</td>
</tr>
<tr>
<td>Areas Certified</td>
<td>Elementary (1-6), General Science (5-8)</td>
<td>k-12</td>
</tr>
<tr>
<td>Science Specialist</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Comfort level when teaching science lessons</td>
<td>Very comfortable</td>
<td>Moderately Comfortable</td>
</tr>
<tr>
<td>Comfort level with using educational computer software</td>
<td>Moderately Comfortable</td>
<td>Moderately Comfortable</td>
</tr>
</tbody>
</table>

The experimental teacher, Maria, had fourteen years of teaching experience. She has a Hispanic background, and her first language is Spanish. She holds a BA degree in Mathematics and Physics and a Master’s degree in Bilingual Teaching. She had been teaching science for ten years and fifth graders for eleven years. She rated her comfort level when teaching science lessons 2 (moderately comfortable) on a scale ranging from
1 (very comfortable) to 5 (very uncomfortable). She is not a science specialist. She had
been teaching math, engineering and foreign language (Spanish) as well. Maria rated her
comfort level with using educational computer software 2 (moderately comfortable) on a
scale ranging from 1 (very comfortable) to 5 (very uncomfortable).

The control teacher, Daniel was a male teacher with six years of teaching
experience. He holds a BA degree in business and a Master’s degree in elementary
education. He had been teaching science for six years and fifth grade for six years. He
rated his comfort level when teaching science lessons 1 (very comfortable) on a scale
ranging from 1 (very comfortable) to 5 (very uncomfortable). He was working as a
science specialist in the school and also as a science teacher trainer for Boston Public
Schools. Daniel rated his comfort level with using educational computer software 2
(moderately comfortable) on a scale ranging from 1 (very comfortable) to 5 (very
uncomfortable).

Maria seems to have a solid mathematics and science background, while Daniel
comes from a business background. However, Daniel felt very comfortable in teaching
science while Maria felt moderately comfortable. The reason why Maria felt less
comfortable in teaching science might be that she had been teaching math and foreign
language as well, therefore her interest and attention might be stretched thin over science,
math and foreign language. In contrast, Daniel has been teaching only science since he
started teaching.

When I compare the two teachers’ instructional performance in general, Daniel’s
teaching tended to be more aligned with inquiry-based teaching as described in science
education reform documents such as the National Science Education Standards (NRC, 1996) and Taking Science to School (Duschl, Schweingruber, & Shouse, 2007). Daniel seemed better prepared and more successful in managing the classroom. Daniel used more posters than Maria, and he encouraged his students to read books related to simple machines by displaying them on the display shelf. He appropriately designed the classroom setting as well. In contrast, Maria did not display any books related to simple machines. Her classroom was not optimally designed for supporting student collaboration using LEGO™ pieces. Because of the classroom setting, Maria’s students were easily distracted and tended to lose motivation to participate in the classroom activities. Therefore, Maria had to spend a significant amount of time getting the students to refocus on the task at hand.

Also, since Maria had been teaching math and Spanish as well as science in the same classroom, her focus had been scattered over three subjects, whereas Daniel had been focused only on teaching science. In addition, unlike Daniel, Maria was not a native English speaker. Thus, Maria might have felt less comfortable than Daniel teaching science despite her strong science content background.

**Written Tests**

In the larger research group, written assessments were created to measure fifth graders’ content understanding of simple machines. Both multiple-choice and open ended items were included. All the questions on the written test were scored via a rubric. Several experts including science educators, engineers and psychologists assessed the
written test for content validity. The written test questions were scored by two of the experts who achieved an inter-rater reliability of 0.92.

**Multiple-choice Items**

There were five multiple-choice content questions in the written test. Table 11 displays the multiple-choice items of the written test, the cognitive skills they require based on Sternberg’s triarchic assessment approach, and the rating scale used to score each question. All of the multiple-choice questions required analytical skills to be able to answer them correctly. In addition, question 2 required memory skills as well analytical skills.

Table 11

*Multiple-choice items in the written test, the cognitive skills they require and the rating scale for them*

<table>
<thead>
<tr>
<th>Item number</th>
<th>Format</th>
<th>Cognitive skill</th>
<th>Rating scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 (Twiggy &amp; Sticky)</td>
<td>MC</td>
<td>Analytic /Memory</td>
<td>0-1</td>
</tr>
<tr>
<td>5 (wheel &amp; axle pictures)</td>
<td>MC</td>
<td>Analytic</td>
<td>0-1</td>
</tr>
<tr>
<td>6 (knife)</td>
<td>MC</td>
<td>Analytic</td>
<td>0-1</td>
</tr>
<tr>
<td>8 (gear picture)</td>
<td>MC</td>
<td>Analytic</td>
<td>0-1</td>
</tr>
<tr>
<td>9 (screw pictures)</td>
<td>MC</td>
<td>Analytic</td>
<td>0-1</td>
</tr>
</tbody>
</table>

I calculated the effect-size correlation for the post scores of the two groups on the multiple-choice items. The effect-size correlation, $r$, equals 0.1648, which denotes a very low correlation between the post scores of the two groups on the multiple-choice items.
ANCOVA-Group (Design-based vs Inquiry-based). One of the major aims of this study was to learn how LEGO™ engineering-design practices, in comparison with inquiry activities, affect students’ content learning of a science topic, namely simple machines. The goal was to test whether the design-based or the inquiry-based units better helped students to perform and generate explanations on the written test items. By calculating a separate analysis of covariance (ANCOVA) on students’ post multiple-choice assessment, the impact of group (the design-based and the inquiry-based curricular units) was determined. For ANCOVA, group was the fixed factor and the appropriate pre-score on multiple-choice items was the covariant. The results of the ANCOVA analysis for group are shown in Table 12. The results indicated that neither the effect of the MCPreSum covariant (F = 1.688, p = 0.198) nor the effect of group (F = 2.014, p = 0.16) is significant at p < 0.05 level. These findings suggest that using the Design a People Mover: Simple Machines unit for teaching simple machines to fifth graders did not result in outcomes significantly different from the FOSS’s Lever and Pulleys unit in terms of students’ analytical learning.

Table 12

ANCOVA results having “MCPostSum” as the dependent variable, “MCPreSum” as the covariate, and “group” as the fixed factor

<table>
<thead>
<tr>
<th>Source</th>
<th>Type III Sum of Squares</th>
<th>Df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrected Model</td>
<td>3.783¹</td>
<td>2</td>
<td>1.891</td>
<td>1.808</td>
<td>.171</td>
</tr>
<tr>
<td>Intercept</td>
<td>166.877</td>
<td>1</td>
<td>166.877</td>
<td>159.488</td>
<td>.000</td>
</tr>
<tr>
<td>MCPreSum</td>
<td>1.766</td>
<td>1</td>
<td>1.766</td>
<td>1.688</td>
<td>.198</td>
</tr>
</tbody>
</table>
a. $R^2 = .045$ (Adjusted $R^2 = .020$); ** $p < .005$

**ANCOVA-Gender.** Moreover, I investigated whether gender had an impact on students’ performance on the multiple-choice questions. By calculating a separate analysis of covariance (ANCOVA) on students’ post multiple-choice assessment, the impact of gender was determined. For ANCOVA, gender was the fixed factor and the appropriate pre-score on multiple-choice items was the covariant. The results of the ANCOVA analysis for gender are shown in Table 13. The results indicated that there is no significant effect of gender ($F = 0.002, p = 0.968$) on students’ scores on multiple-choice items in the post-test. These findings suggest that female students did not achieve outcomes significantly different from male students in terms of their analytical learning.

Table 13

**ANCOVA results having “MCPostSum” as the dependent variable, “MCPreSum” as the covariate, and “gender” as the fixed factor**

<table>
<thead>
<tr>
<th>Source</th>
<th>Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrected Model</td>
<td>1.677a</td>
<td>2</td>
<td>.839</td>
<td>.781</td>
<td>.462</td>
</tr>
<tr>
<td>Intercept</td>
<td>164.902</td>
<td>1</td>
<td>164.902</td>
<td>153.536</td>
<td>.000**</td>
</tr>
<tr>
<td>MCPresum</td>
<td>1.660</td>
<td>1</td>
<td>1.660</td>
<td>1.546</td>
<td>.218</td>
</tr>
<tr>
<td>Gender</td>
<td>.002</td>
<td>1</td>
<td>.002</td>
<td>.002</td>
<td>.968</td>
</tr>
<tr>
<td>Error</td>
<td>81.627</td>
<td>76</td>
<td>1.074</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
R Squared = .020 (Adjusted R Squared = -.006); ** p < 0.005

Female and male students’ mean scores on multiple-choice questions in the pre- and post-tests are shown in Figure 22 below. A total of thirty-two female and forty-seven male students from both groups took the pre- and post-test. The figure shows that male students did better than female students on multiple-choice items in both the pre- and post-tests. However, female students’ post mean score got very close to males’. Male students had a mean score of 2.37, while female students had a mean score of 2.04 in the pre-test. Correspondingly male students’ had a mean score of 3.30, while female students’ had a mean score of 3.27 in the post-test. The ANCOVA results for gender and female and male students’ mean scores on the tests indicate that female students’ increase rate on their scores from pre-test to post-test was higher than that of male students although it was not significant under p < 0.05 level.
Paired T-tests. In addition to ANCOVA analysis, I ran paired t-test analyses for the control group and the experimental group and across groups separately. I paired students’ sum of pre-test scores on multiple-choice items with their sum of post-test scores on the same items for both groups. I also paired students’ pre-scores and post-scores in one group separately to their counterparts in the other group. The paired t-test results are given in Table 14.

Table 14

*Paired differences in students’ scores on multiple-choice items*

<table>
<thead>
<tr>
<th>Combined Pairs</th>
<th>N</th>
<th>M</th>
<th>SD</th>
<th>SEM</th>
<th>T</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCpre Exp - MCpost Exp</td>
<td>53</td>
<td>-.924</td>
<td>1.32</td>
<td>.181</td>
<td>-5.10</td>
<td>.000**</td>
</tr>
</tbody>
</table>

Figure 22. Pre and post mean scores of students from both the control and the experimental groups on multiple-choice questions.
The paired t-test results indicated that in both the experimental group (t = -5.10 and p = 0.000) and the control group (t = -3.82, and p = 0.001) students’ scores on multiple-choice items increased significantly.

In addition, I calculated effect-size correlations for the first and the second pairs. The effect-size correlation, r, values for both the MCpre Exp - MCpost Exp pair (where r = 0.4006) and the MCpre Cont - MCpost Cont pair (where r = 0.4605) were in the medium high range. Figure 23 shows the gains between the pre- and post-tests on multiple-choice items, with the control group (Walnut Elementary School students) showing greater gains. The experimental group had a mean score of 2.25 on the pre-test and 3.18 on the post-test, while the control group had a lower mean score which was 2.19 on the pre-test and a greater mean score which was 3.52 on the post-test.
**Figure 23.** Pre and post mean scores of students from both the control and the experimental groups on multiple-choice questions.

**Comparisons of Students’ Scores on Each Multiple-choice Item.** The first multiple-choice item was about inclined planes. In question 2, students were asked to choose the right reason why Twiggy’s job is easier than Sticky’s. In the pre-test 51.9% of the experimental students from [Peanut] Elementary School chose the correct answer, “a” which suggests that “Twiggy is using an inclined plane. It helps her move the box to the table with less effort.”, while 81.8% of students chose it in the post test. From the control school, [Walnut] Elementary School, 53.6% of the students chose the correct answer in the pre-test, and that increased to 87.2% in the post-test. The second popular answer for both of the groups was “b”, which suggests “Twiggy is using a wedge. It helps her move the box to the table with less motion.” In the pre-test 40.7% of the experimental group and 39.3% of the control group chose this answer. However, in the post test only 3.6% of the experimental group and 5.1% of the control group chose this answer. Distributions of students’ answers to the inclined plane question in the pre-test and the post-test are given for both groups in Figure 24.
Figure 24. Distributions of students’ answers to the inclined plane question in the pre-test and the post-test for (a) for the experimental group and (b) for the control group.

The second multiple-choice question in the tests was a wheel and axle question. In this question, students are given pictures of four real life objects, including a cd, a Jack in the box handle, a door knob and a bicycle handlebar. Students were asked to choose the ones that are examples of wheel and axles. All of these objects except the cd are simple machines. A student gets 0.25 if she/he did not circle the cd and an additional 0.25 for circling any of the other three objects, for a maximum score of 1. For the experimental and the control groups, the distribution of students’ answers to the wheel and axle question in the pre-test and the post-test are given in Figure 25. The number of students who scored 0.5 or less decreased and the number of students who scored 0.75 and 1 increased from pre-test to post-test in both groups. For the control group, increases on the number of students who scored 0.75 and 1 were more dramatic than that of the experimental group.

Figure 25. Distributions of students’ answers to the wheel and axle question in the pre-test and the post-test for (a) the experimental group and (b) the control group.
In another multiple-choice question, students were asked to identify what kind of a simple machine a knife is. For the experimental and the control groups, the distribution of students’ answers to the knife question in the pre-test and the post-test are given in Figure 26. In the pre-test, the most popular answer for the experimental group was “wedge” (40.4 %), while it was “inclined plane” for the control group (43.5 %). Only 26.1 % of the control group correctly chose wedge. In the post test, the percentage of the experimental students who correctly identified a knife as a wedge increased to 67.9 %, whereas for the control group, it increased to 86.8 %, which represents a more dramatic increase.

![Figure 26. Distributions of students’ answers to the knife question in the pre-test and the post-test for (a) the experimental group and (b) the control group.](image)

The question involving gears in the test was multiple-choice as well. In this question, students were shown a gear train showing two gears connected and were asked to identify what this gear train can be used for. For the experimental and the control groups, the distribution of students’ answers to the question about gears in the pre-test and the post-test are given in Figure 27. In the pre-test, 61.5 % of the experimental group
and 80% of the control group chose the right answer: (b), “gears change the speed of spinning”. In the post test, the percentage of correct answers increased to 71.9% in the experimental group, while it decreased to 68.4% in the control group. In the control group, the percentage of students who chose (c), “pull things to a higher height” increased from 15% to 21.1%.

**Figure 27.** Distributions of students’ answers to the gears question in the pre-test and the post-test for (a) the experimental group and (b) the control group.

The last multiple-choice question in the test was about screws. In this question, students are given pictures of four objects and they are asked to circle the object that is an example of a screw. For the experimental and the control groups, the distribution of students’ answers to question about screws in the pre-test and the post-test are given in Figure 28. The pictures included (a) a see-saw, (b) a hammer, (c) stairs, and (d) a tire. In the pre-test, only 9.8% of the experimental group identified stairs as an example of screws, and this percentage increased to 26.5% in the post-test. The most popular answer for the experimental group in both the pre- and post-test was “hammer”. In contrast, “Stairs” were the most popular answer for the control group in both the pre- and post-test.
In the pre-test, 38.31% of the control group chose stairs, whereas it increased to 55.6% in the post-test.

![Figure 28](image)

**Figure 28.** Distributions of students’ answers to the wheel and axle question in the pre-test and the post-test for (a) the experimental group and (b) the control group.

**Open-ended Items**

There were five open-ended content questions in the written test. Table 15 displays the open-ended items of the written test, the cognitive skills they require based on Sternberg’s triarchic assessment approach, and the rating scale used to score each question. All of the open-ended questions required practical skills to be able to answer them correctly. In addition, question 11 required creative skills as well as practical skills.

Table 15

<table>
<thead>
<tr>
<th>Item number</th>
<th>Format</th>
<th>Cognitive skill</th>
<th>Rating scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (quarter vs. screwdriver)</td>
<td>OE</td>
<td>Practical</td>
<td>0-2</td>
</tr>
</tbody>
</table>
I calculated the effect-size correlation for the post scores of the two groups on the open-ended items. The effect-size correlation, $r$, was 0.1648, which denotes a very low effect between the post scores of the two groups on the open-ended items.

**ANCOVA-Group (Design-based vs Inquiry-based).** One of the major aims of this study was to learn how LEGO™ engineering-design practices, in comparison with inquiry activities, affect students’ content learning of a science topic, namely simple machines. The goal was to test whether the design-based or the inquiry-based units better helped students to perform and generate explanations on the written test items. By calculating a separate analysis of covariance (ANCOVA) on students’ post open-ended assessment, the impact of group (the design-based and the inquiry-based curricular units) was determined. For ANCOVA, group was the fixed factor and the appropriate pre-score on open-ended items was the covariant. The results of the ANCOVA analysis for group are shown in Table 16. The results indicated that the effect of group ($F = 0.695, p = 0.407$) is not significant at $p < 0.05$ level. However, the effect of the OEPreSum covariant ($F = 19.573, p = 0.000$) is significant at $p < 0.005$ level. These findings suggest that using the Design a People Mover: Simple Machines unit for teaching simple machines to fifth graders did not result in outcomes significantly different from the FOSS’s Lever and
Pulleys unit in terms of students’ practical learning. In addition, it is seen that students’ post scores on open-ended items are correlated with their scores in the pre-test.

Table 16

ANCOVA results having “OEPostSum” as the dependent variable, “OEPreSum” as the covariate, and “group” as the fixed factor

<table>
<thead>
<tr>
<th>Source</th>
<th>Type III Sum of</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
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<tr>
<td>Corrected Model</td>
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<td>2</td>
<td>29.382</td>
<td>10.981</td>
<td>.000**</td>
</tr>
<tr>
<td>Intercept</td>
<td>393.129</td>
<td>1</td>
<td>393.129</td>
<td>146.926</td>
<td>.000**</td>
</tr>
<tr>
<td>OEPreSum</td>
<td>52.371</td>
<td>1</td>
<td>52.371</td>
<td>19.573</td>
<td>.000**</td>
</tr>
<tr>
<td>Group</td>
<td>1.858</td>
<td>1</td>
<td>1.858</td>
<td>.695</td>
<td>.407</td>
</tr>
<tr>
<td>Error</td>
<td>203.352</td>
<td>76</td>
<td>2.676</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>2097.188</td>
<td>79</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrected Total</td>
<td>262.117</td>
<td>78</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> R Squared = .224 (Adjusted R Squared = .204); ** p < 0.005

ANCOVA-Gender. Moreover, I investigated whether gender had an impact on students’ performance on open-ended questions. By calculating a separate analysis of covariance (ANCOVA) on students’ post open-ended assessment, the impact of gender was determined. For ANCOVA, gender was the fixed factor and the appropriate pre-score on open-ended items was the covariant. The results of the ANCOVA analysis for gender are shown in Table 17. The results indicated that there was no significant effect of gender (F = 2.415., p = 0.124) on students’ scores on open-ended items in the post-test.
Female and male students’ mean scores on open-ended questions in the pre- and post-tests are shown in Figure 29 below. A total of thirty-two female and forty-seven male students from both groups took the pre- and post-test. The figure shows that male students did better than female students in both the pre-test and the post-test. Male students had a mean score of 2.35, while female students had a mean score of 1.37 in the pre-test. Correspondingly, male students’ had a mean score of 5.27, while female students’ had a mean score of 4.16 in the post-interview. The ANCOVA results for gender and female and male students’ mean scores on the interviews indicate that there was no significant difference between female and male students’ increase rates on their scores from pre-test to post-test.
**Figure 29.** Pre and post mean scores of students from both the control and the experimental groups on open-ended questions.

**Paired T-tests.** In addition to ANCOVA analysis, I ran paired t-test analyses for the control group and the experimental group and cross groups separately. I paired students’ sum of pre-test scores on open-ended items with their sum of post-test scores on the same items for both groups. I also paired students’ pre-scores and post-scores in one group separately to their counterparts in the other group. The paired t-test results are given in Table 18.

**Table 18**

*Paired differences in students’ scores on open-ended items.*

<table>
<thead>
<tr>
<th>Combined Pairs</th>
<th>N</th>
<th>M</th>
<th>SD</th>
<th>SEM</th>
<th>T</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>OEpre Exp - OEpost Exp</td>
<td>53</td>
<td>-2.90566</td>
<td>1.78820</td>
<td>.24563</td>
<td>-11.830</td>
<td>.000**</td>
</tr>
</tbody>
</table>
The paired t-test results indicated that in both the experimental group (t = -11.830 and p = 0.000) and the control group (t = -8.436, and p = 0.001), students’ scores on open-ended items increased significantly. The experimental group had a mean score of 2.11 on the pre-test and 5.02 on the post-test, while the control group had lower mean scores which was 2.61 on the pre-test and a greater mean score which was 4.41 on the post-test. Figure 30 shows gains between the pre- and post-tests on open-ended items, with the experimental group, [Peanut] Elementary School students showing slightly greater gains.

![Open-Ended](image)

*Figure 30. Pre and post mean scores of students from both the control and the experimental groups on open-ended questions.*

In addition, I calculated effect-size correlations for both the first and the second pairs. The effect-size correlation, r, values for both the OEpre Exp - OEpost Exp pair
where \( r = 0.6616 \) and the OEpre Cont - OEpost Cont pair where \( r = 0.6343 \) were on the medium high range.

**Comparisons of Students’ Scores on Each Open-Ended Item.** The first open-ended question in the test was about levers. In this question, students were asked if it would be easier to take the top off a paint-can with a quarter or a screwdriver. Both of the groups’ scores in the pre- and post-test for this question are shown in Figure 31. In the pre-test, 56.6% of the experimental students (from the [Peanut] Elementary School) got 1 and the rest got 0 for their answers to this question. In contrast, 77.4% got 1 and 18.9% got 2 for their answers in the post-test. 65.6% of the control students (from the [Walnut] Elementary School) got 1 and the rest got 0 in the pre-test, while 68.8% got 1, 12.5% got 2 and 18.8% got 0 in the post-test.

Most of the students in both groups in the pre- and the post-test chose the screwdriver; however, in the pre-test, they were not able explain why it would be easier with a screwdriver to open the paint can. Students who gave an irrelevant answer such as “because a screwdriver is always used for that” or repeated the question by stating that “it would be screwdriver because it is easier” got no points. Students who discussed the merits of a screwdriver or a quarter that are not fully accurate, but have elements of the force-distance trade-off, got 1 for their answers. Examples of such statements include: “screwdriver, because it has a better grip and is longer to hold” and “the quarter is so small and the edge of the screwdriver is thin”. Students who discussed leverage or the force-distance trade-off of using the screwdriver or the quarter got 2 points. No students from any group were able to give such answers in the pre-test. In contrast, some students
were able to get 2 points for their answers such as “screwdriver, because it is long but there is less effort when you use it too” and “because you are using less force and more distance.”

Figure 31. Distributions of students’ answers to the screw or quarter question in the pre-test and the post-test for (a) the experimental group and (b) the control group.

The results indicate that most of the students from both groups were able to discuss the merits of the screwdriver or a quarter based on their physical properties; however, the majority of the students could not fully understand the concept of leverage and force-distance trade-offs when using real life levers.

In another open-ended question, students were asked to name two things that are simple machines in their houses. Students who were able to name one thing that is a simple machine got 1 point, whereas students who were able to name two things that are a simple machines got 2 points. The experimental and the control groups’ scores in the pre- and post-test for this question are shown in Figure 32. In the pre-test, 71.7 % of the experimental group and 67.9 % of the control group could not name any simple machines at home, while only 7.5 % of the experimental and 10.7 % of the control group were able to name two simple machines. In the post-test, both the experimental and the control
group improved their scores; 39.6% of the experimental group and 25% of the control group were able to name two simple machines at home.

Figure 32. Distributions of students’ answers to the question about the simple machines at home in the pre-test and the post-test for (a) the experimental group and (b) the control group.

From pre-test to post-test, the experimental group improved their scoring more than the control group. Nevertheless, 24.5% of the experimental group and 39.3% of the control group could still not name any simple machines at home. These results indicate that the design-based curriculum was relatively better at making real-life connections to simple machines than the inquiry-based curriculum; however, there is still a need for more real-life connections to simple machines in both curricula.

In another open-ended question, students were asked to give one example of a simple machine that makes pulling heavy things easier and explain how it makes pulling things easier. Students who listed a complex machine or non-machine got 0 point, while students who listed only a pulley, inclined plane, wheel and axle, or gear as the simple machine that helps lift heavy things got 1 point, and students who provided an explanation that uses the simple machine listed to pull a heavy object got 2 points.
Distributions of students’ scores in the pre- and post-test on this question for the experimental and control groups are shown in Figure 33.

Figure 33. Distributions of students’ answers to the question about simple machines pulling heavy things in the pre-test and the post-test for (a) the experimental group and (b) the control group.

67.9 % of the experimental and 84.6 % of the control group got 0 point in the pre-test, while the majority of both groups (62.4 % of the experimental and 69.2 % of the control group) got 1 point in the post-test. It seems that the control group had a better performance in improving students’ scores in the post-test; however, thirteen of the control students did not take the test or missed this question in the pre-test, so having so many missing values might exaggerate the difference between the pre-test and the post-test.

In another open-ended question, students were asked to think of a way pulleys are used in everyday life, and then draw how the pulley is used and label the pulley in their drawing. If a student did not draw anything or drew something else, he/she did not get
any points. Students who drew a pulley without any explanation, or without labeling the pulley, got 1 point, while students who drew a pulley and explained how it is used by labeling it got 2 points. In the pre-test, 39.6 % got 1 point and 11.3 % got 2 points from the experimental group, while 19.2 % got 1 point and 3.8 % got 2 points from the control group. Distributions of students’ scores on this question in the pre- and post-test for the experimental and control groups are shown in Figure 34.

**Figure 34.** Distributions of students’ answers to the question about pulleys in the pre-test and the post-test for (a) the experimental group and (b) the control group.

The percentage of students who got no points for this question decreased dramatically (From 49.1 % to 17 % for the experimental group and from 76.9 % to 26.9 % for control group). 47.2 % of the experimental group and 34.6 % of the control group were able to get 2 points in the post-test.

The final open-ended question required both practical and creative skills to answer it. In this question, students were asked to label all the simple machines they see in the picture of the bicycle given to them. For each simple machine they labeled,
students got from 0.5 up to 2 points. Distributions of students' scores on this question in the pre- and post-test for the experimental and control groups are shown in Figure 35.

![Figure 35. Distributions of students’ answers to the question about simple machines in a bike in the pre-test and the post-test (a) the experimental group and (b) the control group.](image)

In the pre-test, 51.9% of the experimental group and 70.4% of the control group were not able to label a simple machine on the bicycle. From neither group were any students able to label four simple machines in the pre-test. In contrast, 17% of the experimental group and 22.2% of the control group got 0 and 7.5% of the experimental group and 7.4% of the control group were able to label four simple machines in the post-test.

**Interview Items**

There were five semi-structured questions in the interviews. Each interview question focused on a concept about simple machines. Table 19 displays the concepts that the interview items focused on, the cognitive skills they require based on Sternberg’s triarchic assessment approach, and the rating scale used to score each question. Since the
interview items were semi-structured and each included follow-up questions as well as a main question, they addressed multiple triarchic skills.

Table 19

The concepts that the interview items focused on, the cognitive skills they require and the rating scale for them

<table>
<thead>
<tr>
<th>Item number</th>
<th>Format</th>
<th>Cognitive skill</th>
<th>Rating scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (simple machines)</td>
<td>INT</td>
<td>Analytical/Practical</td>
<td>0-3</td>
</tr>
<tr>
<td>2 (complex machines)</td>
<td>INT</td>
<td>Practical/Creative</td>
<td>0-3</td>
</tr>
<tr>
<td>3 (inclined plane)</td>
<td>INT</td>
<td>Analytical/Practical</td>
<td>0-3</td>
</tr>
<tr>
<td>4 (leverage)</td>
<td>INT</td>
<td>Analytical/Practical</td>
<td>0-3</td>
</tr>
<tr>
<td>5 (gears)</td>
<td>INT</td>
<td>Analytical/Practical</td>
<td>0-3</td>
</tr>
</tbody>
</table>

The effect-size correlation, r, for the post scores of the two groups on the interview items was found to be 0.47 (Cohen’s *d* equals 1.05), which indicates a medium effect between the post scores of the two groups.

**ANCOVA-Group (Design-based vs Inquiry-based).** The goal of the ANCOVA test for the two groups was to check whether the design-based or the inquiry-based units better helped students to perform and generate explanations on the interview items. By calculating a separate analysis of covariance (ANCOVA) on students’ post interview assessment, the impact of group (the design-based and the inquiry-based curricular units) was determined. For ANCOVA, group was the fixed factor and the appropriate pre-score on the interview items was the covariant. The results of the ANCOVA analysis for group are shown in Table 20. The results indicated that the effect of group (\(F = 23.137, p = \))
0.000) is significant at \( p < 0.005 \) level. Also, the effect of the covariant, INTPreSum \( (F = 29.607, p = 0.000) \) is significant at \( p < 0.005 \) level. These findings suggest that using the Design a People Mover: Simple Machines unit for teaching simple machines to fifth graders resulted in outcomes significantly higher than the FOSS’s Lever and Pulleys unit in terms of students’ content learning. In addition, students’ post scores on interview items are highly correlated with their scores in the pre-test.

Table 20

ANCOVA results having “INTPostSum” as the dependent variable, “INTPreSum” as the covariate, and “group” as the fixed factor

<table>
<thead>
<tr>
<th>Source</th>
<th>Type III Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
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<tbody>
<tr>
<td>Corrected Model</td>
<td>95.146(^a)</td>
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<td>47.573</td>
<td>23.349</td>
<td>.000**</td>
</tr>
<tr>
<td>Intercept</td>
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<td>67.964</td>
<td>33.358</td>
<td>.000**</td>
</tr>
<tr>
<td>INTPreSum</td>
<td>60.323</td>
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<td>60.323</td>
<td>29.607</td>
<td>.000**</td>
</tr>
<tr>
<td>Group</td>
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<td>1</td>
<td>47.139</td>
<td>23.137</td>
<td>.000**</td>
</tr>
<tr>
<td>Error</td>
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</tr>
<tr>
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<tr>
<td>Corrected Total</td>
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</tbody>
</table>

\( a. \quad R \text{ Squared} = .625 \) (Adjusted \( R \text{ Squared} = .598 \)); \( ** p < 0.005 \)

ANCOVA-Gender. I also investigated whether gender had an impact on students’ performance in the interview questions. By calculating a separate analysis of covariance (ANCOVA) on students’ post interview assessment, the impact of gender was determined. For ANCOVA, gender was the fixed factor and the appropriate pre-score on
the interview items was the covariant. The results of the ANCOVA analysis for gender are shown in Table 21. The results indicated that there is a significant effect of gender (F = 6.394., p = 0.017) on students’ scores on interview items in the post-test.

Table 21

ANCOVA results having “INTPostSum” as the dependent variable, “INTPreSum” as the covariate, and “Gender” as the fixed factor

<table>
<thead>
<tr>
<th>Source</th>
<th>Type III Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrected Model</td>
<td>67.375a</td>
<td>2</td>
<td>33.687</td>
<td>11.121</td>
<td>.000</td>
</tr>
<tr>
<td>Intercept</td>
<td>95.194</td>
<td>1</td>
<td>95.194</td>
<td>31.425</td>
<td>.000</td>
</tr>
<tr>
<td>INTPreSum</td>
<td>32.313</td>
<td>1</td>
<td>32.313</td>
<td>10.667</td>
<td>.003</td>
</tr>
<tr>
<td>Gender</td>
<td>19.369</td>
<td>1</td>
<td>19.369</td>
<td>6.394</td>
<td>.017</td>
</tr>
<tr>
<td>Error</td>
<td>84.819</td>
<td>28</td>
<td>3.029</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>2754.000</td>
<td>31</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrected Total</td>
<td>152.194</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. R Squared = .443 (Adjusted R Squared = .403);  ** p < 0.005

Female and male students’ mean scores on the pre- and post-interviews are shown in Figure 36 below. A total of eleven female and twenty male students from both groups were interviewed before and after instruction. The figure shows that male students did better than female students in both the pre-interview and the post-interview. Male students had a mean score of 6.55, while female students had a mean score of 5.55 in the pre-interview. Correspondingly male students’ had a mean score of 9.95, while female students’ had a mean score of 7.73 in the post-interview. The ANCOVA results for gender and female and male students’ mean scores on the interviews indicate that male
students increased their scores more from pre-interview to post-interview and were significantly higher than that of female students.

![Interview graph](image)

Figure 36. Pre and post mean scores of female and male students on the interview questions.

In addition, I compared the experimental female students’ scores with the scores of the control female students (Figure 37) and the experimental male students’ scores with that of the control male students (Figure 38). Given the small sample size, the results indicate that both female and male students from the control group scored higher than their counterparts from the experimental group in the pre-interview; however, both female and male students from the experimental group outscored their counterparts from the control group in the post-interview.
Figure 37. Comparison of the experimental and control female students' scores on the pre-and post-interview.

Figure 38. Comparison of the experimental and control male students' scores on the pre-and post-interview.

**Paired T-tests.** In addition to ANCOVA analysis, I conducted paired t-test analyses for the control group and the experimental group and cross groups separately. I
paired students’ sum of pre-interview scores on open-ended items with their sum of post-interview scores on the same items for both groups. I also paired students’ pre-scores and post-scores in one group separately to their counterparts in the other group. The paired t-test results are given in Table 22.

Table 22

*Paired differences in students’ scores on interview items.*

<table>
<thead>
<tr>
<th>Combined Pairs</th>
<th>N</th>
<th>M</th>
<th>SD</th>
<th>SEM</th>
<th>T</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTpre Cont - INTpost Cont</td>
<td>15</td>
<td>-1.60000</td>
<td>1.18322</td>
<td>.30551</td>
<td>-5.237</td>
<td>.000**</td>
</tr>
</tbody>
</table>

** Significant at p < 0.005

The paired t-test results indicated that in both the experimental group (t = -9.406 and p = 0.000) and the control group (t = -5.237, and p = 0.000) students’ scores on interview items increased significantly. The experimental group had a mean score of 5.94 on the pre-interview and 10.19 on the post-interview, while the control group had a lower mean score (6.47) on the pre-interview and an only slightly improved mean score (8.07) on the post-interview. Figure 39 shows the gains between the pre- and post-scores on the interview items, with the experimental group showing greater gains.
Figure 39. Pre and post mean scores of students from both the control and the experimental group on the interview questions.

In addition, I calculated effect-size correlations for the first and the second pairs. The effect-size correlation, r, value for the INTpre Exp - INTpost Exp pair (0.6896) indicates a high effect size; and for the INTpre Cont - INTpost Cont pair (0.4025) indicates a medium high effect size.

Comparisons of Students’ Scores on Each Interview Item. The pre- and post-interviews included five identical, semi-structured questions, and each question focused on a concept about simple machines. The interview questions were scored by using a rubric which is given in Appendix G.

Simple Machines. The first question in the interview focused on the concept of simple machines. Students were asked to define what simple machines are and explain for what purposes they are used. Also, students were shown a pulley, a scissors, a ball and a spoon and were asked to identify whether or not they are simple machines.
Both of the groups’ scores in the pre- and post-interview for the first question are shown in Figure 40. In the pre-interview, 80% of the control group students (from the [Walnut] Elementary School) got 1 and the rest (20%) got 2. In contrast, the experimental group students (from the [Peanut] Elementary School) got various scorings for this question: 22.2% scored 0, 38.9% scored 1, 33.3% scored 2 and 5.6% scored 3. Both of the groups’ scores increased considerably in the post-test. In the experimental group, the majority (66.7%) scored 2 while 11.1% scored 1 and 22.2% scored 3. In the control group, the majority, 60%, scored 2 while 26.7% scored 1 and 13.3% scored 3. Both of the groups increased their scores dramatically. No students in either group got 0 in the post-interview.

Figure 40. Distribution of students’ scores on the first interview question: (a) the experimental group, (b) the control group.

I identified students’ pre- and post-conceptions of simple machines. Phrases that were used by students to explain simple machines during the pre- and post-interviews are listed in Table 23. Students’ pre-conceptions included:
- Simple machines are easier to use
- Simple machines make something easier
- Simple machines are easier to build
- Simple machines are easy machines
- Simple machines are small and simple
- Simple machines help you move stuff
- Simple machines move (heavy) things
- Simple machines are machines that people can make by hand or can build
- Simple machines work manually

The students’ pre-conceptions were mostly determined by their literary meanings. Many students related simple machines either with being simple or making something simple or easy.

Students’ post conceptions included:

- Simple machines help you do things more easily
- Simple machines make work easier
- You can build simple machines on your own
- Simple machines make life/everyday stuff easier
- Simple machines are easier to use
- Simple machines help you use less effort
- Simple machines are easier to build

Table 23

Phrases that were used by students to explain simple machines during the pre- and post-interviews

<p>| simple machines                     | Pre  |  | Post  |
|-------------------------------------|------| |       |
| make something easier               | ✓    | ✓     | ✓    | ✓     |</p>
<table>
<thead>
<tr>
<th>Feature</th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>help you move stuff/heavy things</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>help you use less effort</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>are simple</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>make life simple</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>make work easier</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>are easier to use</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>are simple/easier to make</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>are made out of metal</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>work manually</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>move or rotate</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>are associated with simple tasks</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>are machines that people can make by hand</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>help you use less force or energy</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>make pulling things less work</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>pulleys [single pulley] help you use less effort</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

In the post-interviews, students used the concept of *work* for the first time. Even though they could not explain scientifically how simple machines make work easier, students stated that simple machines make work easier. The following is an example conversation with a student from the experimental school in the pre-interview:

**Researcher:** Have you heard of the term “simple machines”?

**Student 1:** No.

**Researcher:** What do you think is a simple machine?

**Student 1:** Maybe a tool for a robot.

**Researcher:** Can you think of anything else?

**Student 1:** No.
Researcher: Which of the following objects are simple machines?

Student 1: I think this one [pulley] is a sm. I think these three [pulley, scissors and ball] are simple machines.

Researcher: Why?

Student 1: Because this [spoon] is plastic and with plastic you might do nothing, but with metal you might do something [things that are made of metal are simple machines, if they are made of plastic they are not]

Researcher: How about the ball—it’s plastic too?

Student 1: Oh now that I am thinking; I think that these two [scissors and pulley] are only simple machines. Because if I say this [spoon] is plastic, this [ball] is plastic too. Now I can say that these are only simple machines.

This conversation shows that Student 1 thinks that simple machines are things that are made of metal, and things that are made of plastic cannot be simple machines. For example, Student 1 said that the spoon, which is actually a lever, is not a simple machine because it is plastic. Also, Student 1 chose the pulley and the scissors as simple machines because they have metal in them. The following conversation shows the same student’s thoughts during the post-interview.

Researcher: Have you heard of the term “simple machines”?

Student 1: Yeah.

Researcher: What do you think is a simple machine?

Student 1: Simple machines: a pulley, a lever, gears, a wheel and axle, a screw and an inclined plane.
**Researcher:** So where do we use simple machines? or- why do we use them?

**Student 1:** To make something easier.

**Researcher:** To make what easier?

**Student 1:** Ohh, I forgot a wedge too. You can use a wedge to cut something and you make something complex. Simple machines make it a little easier.

**Researcher:** Which of the following objects are simple machines?

**Student 1:** This one because it is a pulley.

**Researcher:** Why do we use pulleys?

**Student 1:** We use pulleys; you see those things right there on the windows. It has a pulley in there and you go down [imitating closing or opening the shades]. A pulley is to make something easy. Like there is something from the other side; you put a pulley; and you grab the pulley; and it comes to you.

**Researcher:** What else is a simple machine here?

**Student 1:** The scissors because the scissors is a wedge to cut something.

**Researcher:** How about the spoon?

**Student 1:** No.

**Researcher:** How about the ball?

**Student 1:** No.

In this conversation Student 1 shows a relatively better understanding of simple machines. He no longer has the idea that simple machines are only made out of metal. Although it is not a complete description, Student 1 described simple machines as machines that help us do complex tasks more easily. He described how a wedge and a
pulley can help us do complex things such as cutting something or closing or opening the shades more easily. Student 1 counted all seven types of simple machines; however, he still could not identify the spoon as a lever.

The following is an example conversation with a student from the control group in the pre-interview:

**Researcher:** Have you heard of the term “simple machines”?

**Student 2:** Yeah.

**Researcher:** What do you think is a simple machine?

**Student 2:** I think it means like technology and how stuff are put together; simple and machines. Yeah.

**Researcher:** Why do we use simple machines? What is the purpose of using simple machines?

**Student 2:** I really don’t know why we use simple machines.

**Researcher:** Do you know any simple machines?

**Student 2:** Maybe like refrigerators, maybe RC cars and legos.

**Researcher:** Which of the following objects are simple machines?

**Student 2:** All of them are simple machines.

**Researcher:** So why do you think a ball is a simple machine?

**Student 2:** Ball is a simple machine because it is kind of simple; it is round

**Researcher:** Why do we use the ball?

**Student 2:** For playing

**Researcher:** Why do you think that the spoon is a simple machine?
**Student 2:** Spoon does not require very hard technology.

**Researcher:** How about this one [pulley]?

**Student 2:** That is a simple machine because it is used for holding a string and like you turn it, it moves around. You use it to hang clothes. It is kind of simple.

**Researcher:** How about the scissors?

**Student 2:** The scissors I think is a simple machine because it is basically using two lines; one is sharper. When it closes, it cuts.

This conversation shows that Student 2 defines simple machines in terms of the words *simple* and *machine*, and relates them to technology probably because of the word *machine*. The student gave refrigerators, RC cars and legos as examples of simple machines. Refrigerators and RC cars have characteristics of machines and legos have characteristic of simplicity. Student 2’s definition of simple machines affects on his decisions about whether or not an object is a simple machine. For example, Student 2 thought that the spoon is a simple machine because it does not require very hard technology to use it or to produce it. In the same way, Student 2 identified the ball, the pulley and the scissors as simple machines because they are simple.

Students 2 had a different approach to simple machines in the post-interview. The student got 1 in the pre-interview, but increased his scoring to 3 in the post-interview. The following conversation shows Student 2’s thoughts during the post-interview:

**Researcher:** Have you heard of the term “simple machines”?

**Student 2:** Yeah.

**Researcher:** What do you think is a simple machine?
**Student 2:** Simple machines make everyday stuff more easy to do like a pulley. It makes [it] easier to pull stuff, and a lever it is easier to lift stuff and a wedge it is easier to like carry up stuff because of its angle.

**Researcher:** How do you think that they make everyday stuff easier?

**Student 2:** It is like; if you are going to lift a heavy weight you need a wedge to push it up easier, and you use less Newtons of force.

**Researcher:** Less Newtons of force?

**Student 2:** Yeah

**Researcher:** What simple machines do you know?

**Student 2:** Lever, pulley, wheel and axle, screw, and wedge. I think that’s it.

**Researcher:** Which of the following objects are simple machines?

**Student 2:** All of them.

**Researcher:** Why do you think the spoon is a simple machine?

**Student 2:** Because it has a curved surface to scoop something. It is kind of like a lever.

**Researcher:** So where is the fulcrum?

**Student 2:** The fulcrum would be where I am holding it; right here.

**Researcher:** How about the ball?

**Student 2:** The ball is a wheel I think, because it is round and it is easier to move.

**Researcher:** How about this one [pulley]?

**Student 2:** This is a pulley and it makes lifting easy; because when you have a string, you can lift stuff.
**Researcher:** So let’s say you put a string and a load right here and you pull the other end of the string down, do you use less force?

**Student 2:** Yes.

**Researcher:** How much less?

**Student 2:** Like half of the force that you use to pick it up.

**Researcher:** How about the scissors?

**Student 2:** Scissors is a lever because the fulcrum is here and the load is over here.

**Researcher:** So what is the purpose of using simple machines?

**Student 2:** To make everyday stuff like lifting a heavy weight easier.

In this conversation Student 2 stated that simple machines make everyday stuff easier to do, and he gave uses of pulleys, levers and wedges as examples where simple machines make everyday stuff easier. Student 2 stated “if you are going to lift a heavy weight you need a wedge to push it up easier, and you use less Newtons of force.” In this sentence, the student shows an understanding that simple machines can reduce the force we use. Also, the student defined use of an inclined plane, but named it as a wedge which is not very different from an inclined plane.

Student 2 was able to identify the spoon and the scissors as levers and the pulley, but categorized the ball among simple machines as a wheel. The ball can serve as a wheel, but it is not a wheel and axle. In addition, the student stated that the pulley reduces the force needed to lift an object by half; however, the pulley was a fixed pulley which does not reduce force at all, but only changes the direction of the force.
**Complex machines.** The second question in the interview focused on the concept of complex machines. Students were asked to define what the difference is between simple machines and complex machines. Also, students were asked to give examples of complex machines.

Both the experimental and the control groups’ scores in the pre- and post-interview for the second question are shown in Figure 41. In the pre-interview, students from the experimental group got either 0 or 1. However, in the post test, 33.3% got 1, 61.1% got 2, and 5.5% got 3 while no students got 0. The experimental group improved their scores dramatically from pre-interviews to post-interviews. In contrast, this was not the case for the control group. In the pre-interview, 13.3% of the control group got 0, 80% got 1 and 6.7% got 2. In the post-interview, the percentage of the students who got 1 decreased 20 points, while the percentage of students who got 0 increased by 20 points and the percentage of students who got 2 remained the same (6.7%).

*Figure 41.* Distribution of students’ scores on the second interview question: (a) the experimental group, (b) the control group.
Since the control curriculum, FOSS, *Levers and Pulleys* did not include teaching the concept of complex machines among its objectives, it is understandable that the control group did not improve their scores on this question. Also, phrases that are used by students to explain complex machines during the pre- and post-interviews were listed in Table 24. Whether before or after the instruction, students related complex machines with being complicated and hard to use. Experimental students improved their understanding of complex machines from pre-interviews to post-interviews. They abandoned the idea of defining complex machines as something made out of plastic or as something related to carrying and adopted instead the idea that complex machines help you more than simple machines and that they have two or more simple machines in them. In contrast, the control group showed no improvement at all from pre-interviews to post-interviews. In the pre-interviews, the control students thought that complex machines do not use force. Likewise, in the post-interviews, they thought that complex machines use more force than simple machines and make work harder.

Table 24

*Phrases that were used by students to explain complex machines during the pre- and post-interviews*

<table>
<thead>
<tr>
<th>complex machines</th>
<th>Pre</th>
<th>Post</th>
</tr>
</thead>
<tbody>
<tr>
<td>have more parts</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>help you more than simple machines</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>have two or three simple machines</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>more advanced than simple machines</td>
<td></td>
<td></td>
</tr>
<tr>
<td>complex/hard to use</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
Inclined Planes. The third question in the interview focused on the concept of inclined planes and the force-distance trade-off involved in using them. Students were shown the picture of Twiggy and Sticky as it appears in the first multiple-choice question and were asked to explain why Twiggy’s job is easier than Sticky’s (See Appendix F for the question). The distribution of students’ scores on this question is shown in Figure 42.

![Figure 42](image)

*Figure 42. Distribution of students’ scores on the third interview question: (a) the experimental group, (b) the control group.*
In the pre-interview, the majority of both groups (70.6% of the experimental and 60% of the control group) got 1, 29.4% of the experimental and 40% of the control group got 2, and no students from either group got 3. Although both of the groups significantly improved their scores in the post-interview, the experimental group did slightly better than the control group. The percentage of students who got 1 dropped to 17.6% in the experimental group and 26.7% in the control group. 52.9% of the experimental and 60% of the control group got 2, and 29.4% of the experimental and 13.3% of the control group got 3 in the post-interview.

Phrases that were used by students to explain why Twiggy’s job was easier than Sticky’s to move the box to the top of the table during the pre- and post-interviews are listed in Table 25. Acceptable answers are represented with thick symbols, whereas unacceptable answers are represented with cross symbols. In the pre-interview, both of the groups have acceptable and unacceptable conceptualizations. For example, students from both groups asserted that Sticky does more work or “spends more energy than Twiggy”, which are not scientifically acceptable assertions. Phrases such as “pushing up is easier than lifting” and “pushing it up requires less force” are acceptable, but incomplete. The ideal answer would be: “Twiggy uses an inclined plane which helps him use less force but cover more distance”. In the post-interview, there were students from both groups who gave complete answers. Experimental students, who before instruction asserted that Sticky’s job (picking the box up) is more work managed to correct this misunderstanding; however, some control students held on to this idea even after the
instruction. The only unacceptable answer given by the experimental group in the post-interview was “rolling up is easier than carrying the box up”.

Table 25

*Phrases that were used by students during the pre- and post-interviews to explain why Twiggy’s job was easier than Sticky’s when moving the box to the top of the table*

<table>
<thead>
<tr>
<th>Twiggy and Sticky (inclined planes)</th>
<th>Pre</th>
<th>Post</th>
</tr>
</thead>
<tbody>
<tr>
<td>pushing up is easier than lifting</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>sliding up is easier than carrying the box up</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>ramp helps twiggy not to put so much force</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>pushing it up requires less force</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Twiggy uses less force but more distance</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>picking up is more work</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>rolling up is easier than carrying it up</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>picking the box up is heavier</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Sticky uses more energy than Twiggy</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>the platform gives the box an easy access to the table</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>pushing up doesn’t take much energy</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Twiggy doesn’t struggle with picking it up</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Twiggy’s effort is stretched out</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Levers.* The fourth question in the interview focused on the concept of levers and the force-distance trade-off involved in using them. Students were given two different size levers that were built by using LEGO™ materials. Both of the levers had identical weights on one hand. Students were asked to pick the lever that would lift the weight with the least amount of effort (i.e. force) when they push on the other end of the lever
and to explain their answer. The distribution of students’ scores on this question is shown in Figure 43.

**Figure 43.** Distribution of students’ scores on the fourth interview question: (a) the experimental group, (b) the control group.

Phrases that were used by students during the pre- and post-interviews to explain why one of the levers would help us use less force to lift a heavy weight are listed in Table 26. Acceptable answers are represented with thick symbols, whereas unacceptable answers are represented with cross symbols. In the pre-interview, both of the groups mostly possessed unacceptable conceptualizations. Each group had only one acceptable assertion together with four or five unacceptable conceptualizations. The only acceptable explanation asserted by the experimental group students was “The bigger one because this side [lever arm] is bigger than this side [load arm].” Similarly, some students from the control group asserted that “The longer one has more weight on this side (lever arm),” so it will be easier to push down this side to lift the weight up.

Many students from both groups proposed inaccurate and unacceptable ideas during the pre-interviews. Focused on the speed of the levers, some students from the experimental group claimed that the smaller lever requires less force to lift the object,
while others claimed that the bigger lever requires less force to lift the object. Some
others from the experimental group focused on the mass of the levers and claimed that
the bigger the lever is, the greater the force it requires. Similarly, some students from the
control group focused on the size and the speed of the levers. Additionally, a few students
from the control group picked the longer lever because the point that you push down was
far away from the load. The same idea existed among students from both groups during
the post-interviews as well. Probably, students misunderstood the fact that the distances
from the fulcrum to the load and the effort are the determinant factors to decide which
lever requires less effort to lift the weight. Therefore, teachers need to explain this fact
more clearly while they are teaching.

In the post interviews, the experimental group proposed more acceptable claims
than the control students. There were a couple of students from the experimental group
who claimed that the longer lever requires less force but more distance since its lever arm
is longer than its load arm. Some students from both the groups focused still on the size
of the levers. The levers that were used during the interviews were made out of LEGO™
materials, thus the experimental group was familiar with those levers. Therefore, this
might have an effect on students’ performance on this item.

Table 26

*Phrases that were used by students during the pre- and post-interviews to explain why
one of the levers would help us use less force to lift a heavy weight.*

<table>
<thead>
<tr>
<th>Levers</th>
<th>Pre</th>
<th>Post</th>
</tr>
</thead>
<tbody>
<tr>
<td>The longer one has more weight on this side</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
(lever arm)

The longer one has less force but more distance
(this side [lever arm] is longer than the other side) ✓

The shorter lever has this side [effort arm] shorter ✓

Bigger one because this side [lever arm] is bigger than this side [load arm] ✓

The yellow part is farther away from the fulcrum on the longer lever ✓

| The longer one is far away from the load | X | X | X |
| The shorter one is faster (easier)        | X | X |
| The shorter one does not need that much energy or force and it is easier to lift | X | X |
| The longer one is heavier [requires more force] | X | X |
| You have to push the longer one down a lot | X |
| The longer one goes faster (easier)       | X |
| The longer one can lift the weight [stronger] | X |
| The shorter one because you have less distance to move the weight | X |
| The longer lever because it goes higher  | X |
| The shorter lever because it is lighter | X |
| The bigger lever is holding more weight  | X |

**Gears.** The last question in the interview focused on the concept of gears and the purposes of using them. Students were shown a LEGO™ gear train that has three gears of different sizes and colors connected to each other. The red gear had twenty-four teeth, while the white gear had eight and the green gear had forty teeth. Students were asked to guess spinning directions of the gears when the red gear was spun to one direction, rotation numbers of the gear when the red gear rotated once, and their spinning velocities.
Students were also asked to explain why gears are used in real life. The distribution of students’ scores on this question is shown in Figure 44. Both the experimental and the control groups improved their scores from pre-interview to post-interview. In the pre-interview, the most frequent score that students got was 1 for the experimental group (37.5 %) and the control group (53.3 %); however, the most frequent score for both the groups (56.3 % of the experimental and 60 % of the control group) was 2 in the post-interview.

**Figure 44.** Distribution of students’ scores on the fifth interview question: (a) the experimental group, (b) the control group.

Phrases that were used by students to explain the functioning of gears during the pre- and post-interviews are listed in Table 27. Acceptable answers are represented with thick symbols, whereas unacceptable answers are represented with cross symbols. In the pre-interview, both groups have acceptable and unacceptable conceptualizations. In general, students were successful in explaining the purposes of using gears. For example, in both pre- and post-interviews, in both groups there were students who stated that gears are used to control speed. Also, in both pre- and post-interviews, in both groups there were
students who thought that small gears make more rotations. From pre-interviews to post-interviews, some students from the experimental group adopted the idea that the biggest gear rotates slowest because it has more teeth, while there were control students who stated this idea in both interviews.

Experimental students’ unacceptable ideas included: “Bigger gear makes more rotations”, “The driver gear is the fastest rotating one”, “The middle gear makes more rotations because it is connecting the two”, and “The middle gear is the slowest rotating one because both gears are holding it back”. All of these ideas were eliminated in the post-interviews. However, there was one experimental student who stated in the post-interview that “the middle gear rotates fastest because the other two gears rotates to the opposite way”. Sharing all the unacceptable ideas with the experimental group in the pre-interviews, the control group had additional unacceptable ideas such as, “the furthest gear to the driving gear rotates slowest”, “heavier gear rotates slower”, and “all the gears make one full rotation.” The control group was able to eliminate only one unacceptable idea: that “all the gears make one full rotation.” All the other unacceptable ideas still existed among the control students in the post-interviews.

Table 27

*Phrases that were used by students during the pre- and post-interviews to explain functioning of gears*

<table>
<thead>
<tr>
<th>Gears</th>
<th>Pre</th>
<th>Post</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smaller gear makes more rotations</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>We use gears to control speed</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Statement</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>---------------------------------------------------------------------------</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>Gears are used to move stuff</td>
<td></td>
<td></td>
</tr>
<tr>
<td>The biggest gear rotates slowest because it has more teeth</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Gears transfer motion</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Bigger gear makes more rotations</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>The middle gear makes more rotations because it is connecting the two</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>The driver gear is the fastest rotating one</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>The middle gear is the slowest rotating one because both gears are holding it back</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>The furthest gear to the driving gear rotates slowest</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Heavier gear rotates slower</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>All the gears make one full rotation</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>The middle gear rotates fastest because the other two gears rotates to the opposite way</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Summary of the Results**

Analyses of both the quantitative and the qualitative data collected in this study show that the design-based *Design a People Mover: Simple Machines* unit was, if not better, as successful as the inquiry-based FOSS *Levers and Pulleys* unit in terms of students’ content learning. Moreover, the experimental group, which learned simple machines with the design-based unit, performed significantly better on the interview questions. In addition, paired t-test results showed that both groups improved their scores significantly from pre-test to post-test on the multiple-choice, open-ended, and interview items.
Comparisons among groups in post-multiple-choice scores while controlling for pre-multiple-choice scores showed that there was no significant differences between groups’ although the control group improved their scoring slightly more than the experimental group. The multiple-choice items were good for testing students’ analytical skills based on Sternberg’s triarchic assessment approach. Comparisons among groups in post-open-ended scores while controlling for pre-open-ended scores showed that there were no significant differences between groups, although the experimental group improved their scoring slightly more than the control group. The open-ended items were good for testing students’ practical skills based on Sternberg’s triarchic assessment approach. Comparisons among groups in post-interview scores while controlling for pre-interview scores showed that the experimental group improved their scores significantly (F = 23.137, p < 0.005) better than the control group. The interview items were good for testing students’ analytical and practical skills based on Sternberg’s triarchic assessment approach.

To make comparisons among male and female students, I ran ANCOVA tests for the multiple-choice, open-ended, and interview scores. In the ANCOVA tests, I held students’ pre-scores as covariates and compared their post scores. In the multiple-choice items, female students improved their scores a little more than male students; however, the difference was not statistically significant. In the open-ended items, male students scored higher than female students in both the pre-test and the post-test; however, male students’ improvement rate was not significantly higher than that of female students. In the interview scoring, male students did better than female students in both the pre-
interview and the post-interview, and their improvement rate was significantly ($F = 6.394, p < 0.017$) higher than that of female students.
CHAPTER 5. CONCLUSIONS AND IMPLICATIONS

A number of national educational policy institutes, including the National Research Council (NRC), the National Academies (NA), the National Science Education Standards (NSES), and the American Association for the Advancement of Science (AAAS), call for increased exposure to engineering and technology in United States schools (AAAS, 1993; NA, 2006; NRC, 1996). Correspondingly, educators suggest integrating engineering design in K–12 science classrooms (Davis & Gibbin, 2002; Douglas et al., 2004; ITEA, 2000; Kolodner, 2002; Pearson & Young, 2002). This study sought to examine how LEGO™ engineering-design curriculum materials, in comparison with inquiry-based curriculum materials, may improve students’ understanding of science content and help them establish accurate conceptions of simple machines.

In this final chapter, I summarize the findings of this study and connect them to the existing literature. I then identify the limitations of the current study and how this study may illuminate the direction of future research. Finally, I end with a discussion of the implications of this work on the design and implementation of science curricula in elementary schools.

Findings

In the design-based, LEGO™-oriented Design a People Mover: Simple Machines unit, engineering-design was used to teach the science of simple machines. In contrast, as its developers claim, the FOSS’s Levers and Pulleys unit focuses on helping students to develop the skills of inquiry and controlled experimentation (Lawrence Hall of Science,
2005). The results of this dissertation, similar to other studies, found that engineering-design can be used effectively to teach science content (Cantrell et al., 2006; Lehrer & Romberg, 1996); and engineering-design activities, which encourage students to practice theoretical scientific principles in everyday contexts (Resnick, Berg, & Eisenberg, 2000), help students to establish accurate conceptions and learn many skills that scientists and designers often use in their professions (Kolodner, 2002).

Through this research, I specifically found that:

The experimental teacher, Maria, finished the engineering design-based curriculum in sixteen hours, while the control teacher, Daniel, finished the inquiry-based unit in fourteen hours. Daniel had to skip the last lesson because he ran out of time. Furthermore, Maria implemented the design-based unit for the second time only, while it was Daniel’s fifth time implemented the inquiry-based unit. Also, the design-based unit included complex machines as an extra content.

Overall both the experimental and control groups’ learning outcomes improved.

There was no significant difference between the experimental and control groups’ improvement in their scores from pre-test to post-test. The control group improved their scoring on the multiple-choice items slightly more than the experimental group did (not significantly different), whereas the experimental group improved their scoring on the open-ended items slightly more than their counterparts.
The experimental group improved their scoring on the interview items significantly more (with moderate to large effect sizes) than the control group did from pre-interviews to post-interviews. Since the interview items required both practical and analytical skills such as solving an open-ended problem, the experimental group improved their open-ended problem solving skills more than the control group.

Overall the number of students’ unacceptable conceptions decreased, whereas the number of students’ acceptable conceptions increased in both the groups. The experimental group performed better than the control group in eliminating unacceptable conceptions and establishing scientifically correct conceptions.

For example, for the interview item that is related to gears, the experimental students had four different types of misconception during the pre-interviews. However, none of the experimental students had those misconceptions during the post-interviews (see Table 27).

There was no gender difference in students’ improvement on the written-tests; however, on the interviews the male students improved their scores more than the female students.

Comparing the LEGO™ design-based unit and the inquiry-based unit on simple machines in terms of students’ content learning, I found that students who were taught simple machines with the LEGO™ design-based curriculum learned the content as well as or better than the students who were taught the content with the inquiry-based curriculum. Design activities provide an opportunity for students to solve real life
problems by engaging in a meaningful inquiry and by employing scientific inquiry procedures (Lehrer & Romberg, 1996).

**Limitations and Future Directions for Research**

While this study provides some evidence that design-based curricular materials can be used for teaching science without sacrificing science content learning, there are clearly some limitations of this study. First, this study followed only two classrooms and two teachers’ enactment of either the design-based or the inquiry-based curriculum with a total of 100 students. Although these two teachers represent different experiences, education backgrounds and beliefs, they cannot represent the full range of how teachers enact curriculum materials. Also, 100 fifth grade students represent a very small part of all the fifth graders in the United States, so they cannot represent the full range of fifth graders’ science learning. Thus, larger scale studies examining students’ science learning by engineering-design activities might provide additional information regarding engineering-design as a context for learning science.

Another limitation of the study was the limited time and duration. The control teacher, Daniel, has been teaching the FOSS’s *Levers and Pulleys* unit for more than four years; however, the experimental teacher, Maria had used the FOSS’s *Levers and Pulleys* unit until she agreed to use the design-based *Design a People Mover: Simple Machines* unit two years ago. She has been working in an Engineering focus elementary school; however, before she started enacting the simple machines unit, engineering activities in her classroom were mostly extracurricular and project-based under the control of third parties. Thus she had little or no experience using engineering design as a context for
teaching science. Thus in the future research, it would be more appropriate to compare teachers who have at least three-four years of experience with design-based science instruction to teachers who have equal experience with inquiry-based science instruction.

Kolodner (2002) identified three major challenges to success in teaching by engineering design: (1) teacher preparation, (2) assessment of skills and student learning, and (3) time management. In this study, the assessment of skills and student learning was not identified as problematic; however, teacher preparation and time management was problematic as expected.

Teachers’ use of curriculum materials can be improved by quality professional development programs, such as the customization of instructional activities (Brown, 2008). Engineering-design is a new instructional method for teachers as well as for their students. To have teachers customize engineering-design as a context for teaching science, they need professional development on the use of engineering design. In particular, having the experience of learning with engineering-design would be helpful for teachers to customize engineering-design. Therefore, a possible direction for future research may be investigating the use of engineering-design as context for teaching science content to pre-service teachers. I anticipate that teachers who learn science content by doing engineering-design activities would be more successful in conducting design-based science instruction.

This study included only two teachers’ enactments of either the design-based or the inquiry-based simple machines units. Thus, I cannot make any claims about how different teachers’ use and enactment of the curricula influence student outcomes. In
future research, teachers with various backgrounds, experiences, and instructional styles should enact the design-based curriculum to better evaluate its influence on students’ science content learning. Also, this study focused only on simple machines. Therefore, claims about the influence of design-based instruction on the students' science learning in general would be weak. This suggests that we need studies that examine how the use of design-based curricular materials in different science content areas and in different grades impacts students’ science content learning.

Implications

The National Academy of Engineering (NAE) and the National Research Council (NRC) conducted an analysis of existing K–12 engineering curricula and report their findings. In their report, *Engineering in K-12 Education*, they list the following potential benefits of including engineering in K–12 schools: improved learning and achievement in science and mathematics, increased awareness of engineering and the work of engineers, understanding of and the ability to engage in engineering design, interest in pursuing engineering as a career, and increased technological literacy (Katehi, Pearson, & Feder, 2009, p. 49-50). The NAE and NRC also report that the small number, small size and uneven quality of current studies prevent them from supporting those claims; therefore, there is a need for much more, much higher quality and outcome-based research on engineering in K-12 schools (Katehi, Pearson, & Feder, 2009).

This research contributes to the research literature in two ways. First, most of the research base has been focused on student learning outcomes rather than the curriculum materials. These studies did not include a comparison group. For example, Cunningham
(2007) of the Boston Museum of Science measured the impact of the “Engineering is Elementary” program which integrates engineering with science content for elementary students but they conducted their study without a comparison group. Similarly, Barnett (2005), Fortus et al. (2004), McKay and McGrath (2007), Penner et al. (1998), and Roth (2001) did not include comparison groups in their studies.

There are a few researchers who included comparison groups in their studies. For example, Bottoms and Anthony (2005) used the NAEP test to measure the impacts of the “Project Lead the Way” (PLTW) course on students’ content learning and used a random stratified comparison group; and Tran and Nathan, (2010) used a state achievement test to measure the PLTW course’s impact on students’ mathematics and science learning.

However, as noted by Katehi, Pearson, and Feder (2009), these studies examined learning outcomes strictly through the use of pre-post multiple-choice exams. In contrast, this study includes a comparison group and does not rely only upon pre-post multiple-choice items. The focus of this study is the impact of a design-based curriculum in comparison to an inquiry-based curriculum on students’ learning outcomes; and students’ learning outcomes were examined not only through pre-post multiple-choice items, but also through open-ended and interview items. For Fetterman (1989), interview is the most important data collection technique that qualitative researchers can use. Similarly, Jakobson, Mäkitalo, and Säljö (2009) investigated whether the research results on students’ understanding of greenhouse effect and global warming are artifacts of the research methods deployed. They found that studies that do not deploy interview as a data collection claimed that students hold misconceptions on greenhouse effect and
global warming; however, when they interviewed students they found that the students do not have such misconception. Jakobson, Mäkitalo, and Säljö conclude that students’ knowledge can be revealed best in communicative and interactive practices with using cultural tools.

The results of this study showed that the experimental students scored comparably on the multiple-choice and opened-items on the pre-post exam, but that they significantly outperformed the control students on the interview items. The interviews were aligned more with the design-based curriculum, and this might have given an advantage to the experimental students. One of the interview items was about complex machines, which was not covered as a context in the inquiry-based unit, and levers and gears used during the interviews were made out of LEGO™ materials. The results may also suggest that the engineering design-based curriculum encourages students to think through how to solve more open-ended problems that require making connections between analytical and practical components in Sternberg’s triarchic approach to intelligence. This is particularly important for engineering education because engineers are expected to take plans and problems that are given to them and create feasible, workable solutions by merging together their analytic ability of design and construction with functionality. Correspondingly, the NAE and NRC see design as the most important feature of engineering and the essential engineering approach to solving problems in which engineers “can integrate various skills and types of thinking—analytical and synthetic thinking; detailed understanding and holistic understanding; planning and building; and
implicit, procedural knowledge and explicit, declarative knowledge” (Katehi, Pearson, and Feder, 2009, p. 37).

The findings of this study include many implications for science education in K-12 schools, especially elementary science education, the future development of elementary science curriculum materials, and in-service and pre-service science teacher preparation. This study suggests that we need to rethink how we teach science content to elementary students, and how to help them learn the content better and establish more accurate conceptions of the content. During the implementation of the units, I observed that the experimental teacher, Maria, had difficulty adopting engineering-design in her teaching. However, despite Maria’s struggles in adapting engineering-design into her teaching, her students learned the content of simple machines as well as or better than their counterparts via the LEGO™ design-based Design a People Mover: Simple Machines unit. These results add to the work of Kolodner (2002) and Pearson and Young (2002) and suggest that engineering-design can be used as a context for teaching science without sacrificing students’ content learning, and with the extra benefit of teaching engineering-design procedures.

Potential dangers of using engineering-design as a context for science education include teacher preparation, assessment of skills and student learning, and time management (Kolodner, 2002). In this study, assessment of skills and student learning was not a big issue; however, teacher preparation and time management were seen as important factors that affect the success of the curriculum. The experimental teacher, Maria, complained many times about being short of time. She also stated a couple times
that she was not very comfortable enacting the design-based curriculum because it was totally new for her. The NAE and NRC report that there is no reliable data on the number of teachers who received pre- or in-service professional training to teach engineering in K-12 schools (Katehi, Pearson, & Feder, 2009). This takes Bers & Postmore (2005) and Taylor’s (2001) implications further and suggests that the idea of using engineering-design as a context for teaching science should be extended to teacher preparation. Pre-service science teachers should be taught scientific concepts and how to teach science via design-based activities. In this way, teachers would become expert users of engineering-design as a context for teaching science in their classroom, and this would help them manage their time wisely while teaching. Also, there should be a link between in-service teachers’ professional development and the curriculum materials they use, because professional development would be more effective if it is related to curriculum materials (Cohen & Hill, 2001). Therefore, in-service teachers should gain experience with design-based instruction by engaging in design activities in their professional development courses.

Finally, these findings suggest that integrating engineering-design in K-12 science education involves not only designing science curricula by using engineering-design as a context to teach the science content, but also reorganizing teacher preparation and teacher’s professional development accordingly so as to include engineering-design.

**Conclusions**

The use of engineering-design as a context for teaching science has real potential to engage elementary school students in solving real life problems and in the engineering-
design process, which is also rich in terms of inquiry. Also, using LEGO™ materials as instructional tools has great potential to add fun and motivation to students’ science learning. The realization of these potentials lies with teachers’ ability to implement engineering-design as a context for their science teaching and their ability to guide and scaffold students during instruction. This requires teachers to have experience with engineering-design activities. Clearly, pre-service teachers’ preparation and in-service teachers’ ongoing professional development are important factors for the potential of engineering-design as a context for science education to be realized.

The findings of this study suggest that it is possible to use engineering-design as a context for science teaching without sacrificing content learning in a way that engages students in real life related engineering-design procedures. In this way, students learn not only the science content, but also how to engage in a meaningful inquiry and employ scientific inquiry procedures (Lehrer & Romberg, 1996). Also, engineering-design activities encourage students to practice theoretical scientific principles in everyday contexts (Resnick, Berg, & Eisenberg, 2000), and help students to develop accurate conceptions and learn many skills that scientists and designers often use in their professions (Kolodner, 2002).

While further research is necessary to investigate how different teachers (from a variety of backgrounds, experiences, and instructional styles) enact design-based curricula, and to explore the use of engineering-design as a context for teaching different science topics, this study does provide an understanding of how an engineering-design curriculum supports students’ content learning and mastery of the scientific concepts.
involved in simple machines. It therefore provides some important implications for elementary science education, the future development of elementary science curriculum materials, and in-service and pre-service science teacher preparation.
CHAPTER 6. REFERENCES


http://search.ebscohost.com.proxy.bc.edu


Retrieved from Education Research Complete database.


American Society for Engineering Education.


http://search.ebscohost.com.proxy.bc.edu


Kolodner, J., Camp, P., Crismond, D., Fasse, B., Gray, J., Holbrook, J., et al. (2003). Problem-Based Learning Meets Case-Based Reasoning in the Middle-School...


Puget sound. Paper presented at the annual meeting of the National Association for Research on Science Teaching.


*Physics Education, 29, 368-374.*
Appendix A. National, State, and District Learning Standards that align with the Simple Machines: Design a People Mover unit.

<table>
<thead>
<tr>
<th>Learning Objectives</th>
<th>National AAAS Benchmarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>By the end of this module, students will be able to:</td>
<td>4.F. 2nd Grade</td>
</tr>
<tr>
<td>1) Explain what the following simple machines do to help humans:</td>
<td>- The way to change how something is moving is to give it a push or a pull.</td>
</tr>
<tr>
<td>a) Levers, which are stiff bars that rotate around fixed points, make it easier to lift a load or apply a force.</td>
<td>- Things move in many different ways, such as straight, zigzag, round and round, back and forth, and fast and slow.</td>
</tr>
<tr>
<td>b) Wheel-and-axes, which are two differently-sized wheels attached to the same axis, are used to make circular motion easier.</td>
<td>4.F.5th Grade</td>
</tr>
<tr>
<td>c) Inclined planes, which are surfaces slanted upwards, lower the effort needed to lift a load.</td>
<td>- Changes in speed or direction of motion are caused by forces. The greater the force is, the greater the change in motion will be. The more massive an object is, the less effect a given force will have.</td>
</tr>
<tr>
<td>d) Wedges, which are two inclined planes joined back to back to form a sharp edge, are used to change the direction of a force and often result in the splitting of objects.</td>
<td></td>
</tr>
<tr>
<td>e) Screws, which are inclined planes wrapped around a cylinder, are used to raise and lower objects and hold objects together.</td>
<td></td>
</tr>
<tr>
<td>f) Pulleys, which are wheels with grooved edges for ropes, are used to change the direction of a pull and make it easier to lift a load.</td>
<td></td>
</tr>
<tr>
<td>g) Gears, which are wheels with teeth around the edge, are used to turn other gears and change the direction, speed, and force of circular motion.</td>
<td></td>
</tr>
</tbody>
</table>

More generally:
Recognize that simple machines help humans by: (a) decreasing the input force and increasing the input distance or (b) increasing the input force and decreasing the input distance needed to do work. Simple machines do not change the amount of work done

2) Identify examples of simple machines in everyday objects.
3) Identify simple machines within complex machines.
4) Choose appropriate simple machines to solve a mechanical problem.
5) a) Define engineering design as the process of creating solutions to human problems through creativity and the application of math and science knowledge.

National Science Education Standards

Content Standard A: Science as Inquiry Pr(K-4)
- Identify a simple problem, propose a solution, implement proposed solutions, evaluate a product or design, communicate a problem, design, or solution

Content Standard B: Position and Motion of Objects Pr(K-4)
- The position and motion of objects can be changed by pushing or pulling. The size of the change is related to the strength of the push or pull.

Massachusetts Frameworks

Grades 3-5, Technology/Engineering
- Identify and explain the difference between simple and complex machines, e.g. hand can opener that includes multiple gears, wheels, wedge gear, and lever.
- Identify relevant design features (e.g., size, shape, weight) for building a prototype of a solution to a given problem.

Somerville Science Benchmarks

Materials & Tools Learning Standards, Grade 4
- Appropriate materials, tools, and machines extend our ability to solve problems and invent.
- Identify and explain the difference between simple
b) List and explain the following steps of the engineering design process:

- i. Identifying a problem
- ii. Researching possible solutions
- iii. Picking the best solution
- iv. Building a prototype
- v. Testing the prototype
- vi. Repeating any steps needed to improve the design

and complex machines, e.g. hand can opener that includes multiple gears, wheels, wedge gear, and lever.

**Materials & Tools Benchmarks, Grade 4**

- Discuss the difference between simple and complex machines (e.g. pulley vs. toy wagon).
### Appendix B. Simple Machines: Design a People Mover unit overview.

<table>
<thead>
<tr>
<th>Lesson Title</th>
<th>Lesson Overview</th>
<th>Lesson Learning Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: What machines help people move?</td>
<td>Students are introduced to the design challenge of building people movers, machines that move people up and over. They consider the pluses and minuses (trade-offs) of these machines.</td>
<td>Define engineering design as the process of creating solutions to human problems.</td>
</tr>
<tr>
<td>2: What are the seven simple machines?</td>
<td>Students explore examples of the seven different simple machines.</td>
<td>Explain that simple machines help humans</td>
</tr>
<tr>
<td>3: What happens when we change a lever’s rotation point?</td>
<td>Students are introduced to the mechanics of levers and the ways levers can help humans. Students are introduced to key lever vocabulary (load, force, distance, rotation point) through the demonstration of a prying lever and the investigation of a weight-lifting lever.</td>
<td>Explain that levers, which are stiff bars that rotate around fixed points, make it easier to lift a load or apply a force.</td>
</tr>
<tr>
<td>4: What are other types of levers?</td>
<td>Students discuss how a lever’s rotation point affects the applied force and distance, and they are introduced to the mechanics of two-armed levers and the ways they can help humans. Students also identify everyday examples of levers.</td>
<td>Explain that levers, which are stiff bars that rotate around fixed points, make it easier to lift a load or apply a force. Identify examples of simple machines (levers) in everyday objects. Identify simple machines (levers) within complex machines.</td>
</tr>
<tr>
<td>5: How do wheel-and-axle systems work?</td>
<td>Students test wheel-and-axle systems of different shapes and sizes to determine which requires the least effort to turn a model food mixer.</td>
<td>Explain that wheel-and-axles, which are two differently-sized wheels attached to the same axis, are used to make circular motion easier. Identify examples of simple machines (wheel-and-axles) in everyday objects. Identify simple machines (wheel-and-axles) within complex machines.</td>
</tr>
<tr>
<td>Lesson Title</td>
<td>Lesson Overview</td>
<td>Lesson Learning Objectives</td>
</tr>
<tr>
<td>--------------</td>
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</tbody>
</table>
| **6: How do inclined planes, screws, and wedges work?** | Students are introduced to the uses of inclined planes, screws, and wedges and the ways they can help humans. Students test inclined planes of varying lengths to determine which requires the least force. Students also find the inclined planes in wedges and screws. | Explain that inclined planes, which are surfaces slanted upwards, lower the effort needed to lift a load. 
Explain that wedges, which are two inclined planes joined back to back to form a sharp edge, are used to change the direction of a force and often result in the splitting of objects. 
Explain that screws, which are inclined planes wrapped around a cylinder, are used to raise and lower objects and hold objects together. 
Identify examples of simple machines (inclined planes, screws, and wedges) in everyday objects. 
Identify simple machines (inclined planes, wedges, screws) within complex machines. |
<p>| <strong>7: How do pulleys work?</strong> | Students are introduced to pulley systems as a means for lifting heavy things to heights above our heads. They explore differently sized pulleys and observe the force and distance of pull with fixed and moveable pulley systems. | Explain that pulleys, which are wheels with grooved edges for ropes, are used to change the direction of a pull and make it easier to lift a load. |
| <strong>8: How do gears change circular motion?</strong> | Students are introduced to the uses of gears and the ways gears can help humans to change the direction, speed, and force of circular motion. If time permits, students also build a gear train that spins a disk fast enough to create an optical illusion. | Explain that gears, which are wheels with teeth around the edge, are used to turn other gears and change the direction, speed, and force of circular motion. |</p>
<table>
<thead>
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</table>
| 9: How can we find simple machines in complex machines?                     | Students analyze complex machines to identify the simple machines within them. Students review the force/distance trade-offs of simple machines and begin the preliminary design of their people movers. | Identify simple machines within complex machines.  
Choose appropriate simple machines to solve a mechanical problem.                                                            |
| 10: What simple machines can be used to create a model people mover?        | Students construct, review, modify, and diagram their model people movers.                                                                                                                                          | Identify simple machines within complex machines.  
Choose appropriate simple machines to solve a mechanical problem.                                                            |
| 11: How do simple machines help us?                                        | Students share their complex machines with other students. A culminating class discussion helps students reflect on their learning about simple and complex machines.                                                    | Identify simple machines within complex machines.  
Choose appropriate simple machines to solve a mechanical problem.                                                            |
Appendix C. A sample lesson plan and engineers’ journal.

science through LEGO engineering

Lesson 7

How do pulleys work?

Suggested Time
One 60-minute session

Lesson Overview
Students will be introduced to pulley systems as a means for lifting heavy things to heights above their heads.

- Exploration question: Introduction to lifting pulley systems
- Partner work: Exploration of LEGO-sized fixed pulley and movable pulley systems
- Demonstration with teacher: Observing the force and distance required for full-sized fixed pulley and movable pulley systems
- Conclusion: Wrap-up discussion

Learning Objectives
By the end of this lesson, students will be able to:

1. Explain what pulleys do to help humans.
2. Pulleys, which are wheels with grooved edges for ropes, are used to change the direction of a pull and make it easier to lift a load.

Vocabulary
Pulley - A smooth surface, usually a wheel with a groove, around which a rope moves. The rope is used to change the direction of a pull and make it easier to lift a load.

Fixed Pulley - A pulley that always stays in one place.

Moveable Pulley - A pulley that can move up and down along the rope threaded around it.

Force - A push or a pull.

Load - The object being lifted or moved by a machine.

Spring Scale - A device, also called a force meter, that uses a hanging spring to measure the amount of a pulling force (e.g., the weight of a hanging object).

Materials
- LEGO weight (heavy black LEGO brick) and LEGO kit
- 45-cm (18-in) length of thin string or unwaxed sloss
- Ruler or measuring tape
- Masking tape
- 1-Newton force meter (spring scale)

For each student
- Engineer’s Journal Part 7
Lesson 7

How do pulleys work?

For the class:
- 5-Newton force meter (spring scale)
- 0.5-liter bottle filled with water
- 2 pulley wheels (provided in supply box)
- Two 6-foot lengths of nylon rope
- One 6-inch length of nylon rope
- Full-sized fixed and moveable pulley demonstration set-up (see instructions below)

Preparation:
- For each student pair, cut a 48-cm (18-in) length of thin string or dental floss. This is for their LEGO-sized pulley investigation.
- Prepare the fixed and moveable pulley systems for the class demonstration:

**FIXED PULLEY:**
1. Find a high location that can support the weight of a hanging 0.5-liter water bottle (wall hook, ceiling hook, coat rack, door, etc.).
2. Tie or hook one pulley to this high location. This will be the FIXED pulley. You will also use this as one of the pulleys for the moveable pulley system.
3. Cut one 6-foot length of rope. Tie one end to the full 0.5-liter water bottle. This will be the string you pull for the FIXED pulley.

**MOVEABLE PULLEY:**
1. Cut another 6-foot length of rope. Tie one end to the same high location to which the fixed pulley is attached. (Alternatively, tie it to the fixed pulley itself.) This will be the rope you pull for the MOVEABLE pulley system.
2. Cut a 6-inch length of rope. Tie one end to the hook of the second pulley (this will be the moveable pulley).
3. Set aside the moveable pulley, water bottle, and 5-Newton spring scale.
Lesson 7  How do pulleys work?

Fixed Pulley Set-Up

START
Load is resting on table or ledge.

Load is lifted to fixed pulley wheel.

FINISH

Distance moved by the load

Pulling Distance

Moveable Pulley Set-Up

Rope is tied to fixed pulley OR to ceiling or wall.

One pulley remains tied to ceiling or wall.

START

One pulley (with load tied to it) is moveable and balanced on table.

Load is resting on table or ledge and is tied to moveable pulley.

FINISH

Load is lifted until pulley wheels touch.

Distance moved by the load

Pulling Distance

With the load hanging freely (not resting on or against anything), use the 5-motion spring scale to measure the pulling force. Make sure you hold your hand still as you read the meter.
Lesson 7

How do pulleys work?

PART I: Introduction to Pulleys and Exploration Question (10 min)

1) Explain that in today’s lesson students will learn how the pulley simple machine helps people do work. Students will explore different kinds of LEGO-sized pulley systems with their partners. Then, you will work as a class to take some force and distance measurements for two full-sized pulley systems.

2) State that a pulley is a smooth surface, usually a wheel with a groove, around which a rope moves. The rope is used to change the direction of a pull and make it easier to lift a load.

3) Have students prepare for today’s investigation by thinking about how they could lift a heavy box above their head. Have students answer the exploration question on page 7-1: “If the person in the picture wants to lift the box up to the star, where should she put the pulley rope?”

4) After 3 to 4 minutes, call on a few students to share their ideas about the placement of the pulley rope. (The person in the picture would need to put the rope over the highest wheel in order to move the box to the star.)

5) Conclude this initial discussion by explaining that pulleys are useful for changing the direction of motion—they help humans move things (e.g., boxes) up by pulling down on a rope. Pulleys make it easier to lift heavy things to high places above our heads.

PART II: Exploring Small and Big Pulley Wheels (30 minutes)

6) Explain that there are two main science questions for today. By finding the answers to these questions, students will learn how to design a pulley for their people mover machine.

7) Write the two science questions on the board or chart paper. They are:
   a. Does the size of a pulley wheel affect how much force it takes to lift a load?
   b. Which pulley takes less force to do a lifting job: a “fixed” pulley or a “moveable” pulley? What about less distance?

8) Students will first explore the question about pulley wheel size by working with their partners on pages 7-2 and 7-3 in their journal.
Lesson 7

How do pulleys work?

9) Take a few minutes to demonstrate how to get started on these pages.
   First, point out that journal page 7-2 shows students the 16 LEGO pieces they need.

10) Second, use the instructions on journal page 7-2 to show how to put together the LEGO-sized pulley systems. The completed set-up should look like this:

11) Third, show how to “test” the pulley system (details on journal 7-3):
   a. Measure how far you must pull the string to lift the weight up to the height of one long beam (15 LEGO holes). (To lift the load up one beam-length with a fixed pulley, you should have to move your hand down the same distance, one beam-length.)
   
   b. Hook the 1-Newton spring scale (force meter) onto the 3-hole beam at the free end of the string. Use this scale to measure how much force it takes to hold the weight at the height of one LEGO beam. Make sure to hold your hand still as you read the force measurement. (To lift the load with a fixed pulley, you should have to pull with a force equivalent to the load’s weight, about 0.5 N.)

12) Distribute a 45-cm (18-inch) length of string, a LEGO weight, and a LEGO kit to each student pair. Allot 20 minutes for students to build their pulley systems and complete the exercises on page 7-2 and 7-3.

13) Conduct a brief discussion about the first science question for the day: Does the size of a pulley wheel affect how much force it takes to lift a load? What differences, if any, did the students find between the small and big wheels when they used them as pulleys?

14) After hearing some ideas, help students understand that the size (diameter) of a pulley wheel does not change the amount of force you need to exert to lift a load up (the “pulling force”), nor does it change the distance you need to pull down to lift a load up (the “pulling distance”).
PART III. Exploring Fixed and Moveable LEGO Pulleys (10 min)

15) Now students will use their LEGO pulley system to explore the second science question for the day: Which pulley takes less force to do a lifting job: a "fixed" pulley or a "moveable" pulley? What about less distance? In a fixed pulley system, like the one the students have already been using, the pulley wheel stays in the same place all the time. In a moveable double pulley system, a second pulley (the 1x2 LEGO beam) moves up and down with the weight.

16) To explore the second science question, students will change their pulley set-up into a moveable double pulley system. Then they will measure how much force and distance are required to lift the weight with that moveable pulley system. Ask students to predict: Will the moveable pulley system take more pulling force than the fixed pulley system? Will it require more pulling distance than the fixed pulley?

17) Demonstrate how to change the LEGO pulley set-up into a moveable pulley system. Use the instructions on journal page 7-4 to guide you.

18) Allot about 10 minutes for students to change their pulley set-ups and make force and distance measurements for the moveable pulleys. Have them record their measurements on page 7-4.

19) Now ask students for their ideas about the second science question. What differences did they find between the fixed pulley system and the moveable pulley system?
   a. To lift the load up one beam-length with a moveable double pulley, you have to move your hand down TWICE the distance, two beam-lengths.
   b. To lift the load with a moveable double pulley, you have to pull with a force equivalent to the HALF the weight of the load, about 0.25 N.

20) Have students to complete the summary questions on page 7-5.
21) Explain that you will now conduct a demonstration with full-sized pulleys to double-check your answers to today’s science questions. Before beginning, follow the Preparation steps on page 7-2 of this lesson plan, and review the figures on page 7-3.

22) As it is feasible, ask students to assist you in carrying out the procedure for exploring the fixed pulley:
   a. Set the water bottle on a table or desk, and pass the 6-foot rope through the “fixed” pulley that you have hung from the wall or ceiling. Hold on to the other end of the string.
   b. Measure the pulling distance: Note the location where your pulling hand begins. Pull on the string so that the bottle travels from the table/desk all the way to the fixed pulley. Measure the distance between where your hand is now and where it started.
   c. Measure the pulling force: Tie the force meter to the free end of the string. Pull the force meter until the bottle is halfway to the fixed pulley, and then hold your hand very still as you take the reading from the force meter.
   d. Direct students to record the pulling distance and pulling force in their journals (page 7-5).

23) To add the moveable pulley:
   a. Remove the bottle from the 6-foot rope.
   b. Tie the bottle to the other (moveable) pulley.
   c. Pick up the free end of the other 5-foot rope, which should be tied at one end to the ceiling/wall or to the fixed pulley.
   d. Pass this rope through the moveable pulley and then back up and over the fixed pulley. Hold on to the free end of the string. (See the picture on the following page.)

24) Repeat step #22 to find the pulling force and pulling distance to lift the bottle from the table/desk all the way up to the fixed pulley. Have students record the data in their journals.

25) Conclude the discussion with a summary of the two pulley systems:
   - Lifting with a fixed pulley: We pull DOWN (or any direction) with force equal to the load, and with distance same as the distance moved by the load. The pulley helps us because we can pull the string down (or sideways, or any direction) instead of pushing the load up.
   - Lifting with a moveable pulley: We pull DOWN (or any direction) with force equal to HALF the load, and with distance DOUBLE the distance moved by the load. The pulley helps us because (1) we can pull the string down (or sideways, or any direction) instead of pushing the load up, and (2) we only need to
Lesson 7

How do pulleys work?

put in half the force.

26) Tie these conclusions into filling out the trade-off chart in the classroom and in the students' Engineering Journal.

27) Have students use page 7-5 to make changes to their people mover design based on what they have learned about pulleys.
TODAY'S EXPLORATION QUESTION: If the person in the picture wants to lift the box up to the star, where should she put the pulley rope?

1) Complete the rope - draw where the rope should go to help her lift the box.

2) Write a sentence to explain why you drew the rope where you did.
**TODAY'S BIG SCIENCE QUESTIONS:**

1. Does the size of a pulley wheel affect how much force it takes to lift a load?
2. Which pulley takes less force to do a lifting job: a "fixed" pulley or a "moveable" pulley? What about less distance?

**INVESTIGATION:** Build a miniature pulley system to investigate how pulleys help us do work.

**STEP 1.** Find these LEGO pieces:

- (1) long axle
- (4) long connector pegs
- (2) short connector pegs
- (2) 15-hole rounded beams
- (2) L-beams
- (1) 3-hole rounded beam
- (1) big wide wheel
- (1) small wide wheel
- (1) bushing
- (1) 1x2 beam with hole

**STEP 2.** Use two short pegs to connect the long 15-hole beams together.

**STEP 3.** Tape the two L-beams of your “tower” to your desk.

**STEP 4.** Slide a long axle through the second-from-top hole of your tower (not the top hole, but the hole underneath it).

**STEP 3.** Use two long pegs to add two L-beams to the bottom of a long beam.

---

7-2

---
**How do pulleys work?**

**STEP 5.** Slide a **small wide wheel** onto one side of the axle. Slide a **big wide wheel** onto the other side of the axle. Use a **bushing** to keep the small wheel in place.

**STEP 6.** Add a 1x2 beam to the top of your LEGO weight.

**STEP 7.** Thread a bit of string through the hole on the 1x2 beam. Insert a **long peg** to hold the string in place.

**STEP 8.** Thread the other end of the string through a hole in the 3-hole rounded beam. Insert a **long peg** to hold the string in place.

**STEP 9.** On the lines below, record your observations of each pulley wheel.

**A.) Using the BIG pulley wheel:**
To lift the load up to the height of ONE BEAM (15 LEGO holes), what distance do you have to pull the string?

```
Pulling distance = _______________
```

To hold the load steady at the height of ONE BEAM (15 LEGO holes), how much force do you have to put in?

```
Pulling force = _______________ Newtons
```

**B.) Using the SMALL pulley wheel:**
To lift the load up to the height of ONE BEAM (15 LEGO holes), what distance do you have to pull the string?

```
Pulling distance = _______________
```

To hold the load steady at the height of ONE BEAM (15 LEGO holes), how much force do you have to put in?

```
Pulling force = _______________ Newtons
```
**STEP 10.** Follow these steps to change your pulley system into a **moveable double** pulley.

A.) Remove the big wheel from the pulley tower.

B.) Remove the long pea from the 1x2 beam on top of the LEGO load.

C.) Thread the string through the 1x2 beam and then up through the top hole of the pulley tower.

D.) With a little bit of string sticking out of the top hole, insert a long peg into the hole. This peg should hold the end of the string in place.

**STEP 11.** To lift the LEGO load with your **moveable double pulley**, wrap the string over the small pulley wheel and move your hand down. Use the questions below to make observations of the moveable pulley system.

To lift the load up to the height of ONE BEAM (15 LEGO holes), what distance do you have to pull the string?

\[
\text{Pulling distance} = \quad \text{__________}
\]

To hold the load steady at the height of ONE BEAM (15 LEGO holes), how much force do you have to put in?

\[
\text{Pulling force} = \quad \text{Newton}s
\]

**SUMMARY:** Circle the word or phrase that best completes the sentence.

(1) The force for lifting a load with a **moveable double** pulley is about ________ the force for lifting a load with a **fixed single** pulley.

\[\text{double} \quad \text{the same as} \quad \text{half}\]

(2) When I pull the string in a **moveable double** pulley system, the load moves ________.

\[\text{the same distance my hand moves} \quad \text{half the distance my hand moves}\]

7-4
Pulleys in Everyday Life: Think of objects in the classroom and at home.

What are some objects or devices that use pulleys?

(For example, a flag pole uses a pulley system to lift a flag.)
How do pulleys work?

People Mover Design: Now that you know more about simple machines, how have your ideas for your LEGO people mover changed? What are your ideas now about how to move your LEGO person up and over using three simple machines?

(Remember that you may only touch the LEGO person yourself before you start the up-and-over move.)

Sketch of Idea:

Written explanation of Idea:

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________
Appendix D. Written test – pre and post- on simple machines.

Name: _____________________________ Date: __________

SIMPLE MACHINES – QUESTIONS

1) Would it be easier to take to top off a paint can with a quarter or a screwdriver?

Circle one.

Quarter: 

Screwdriver:

Explain why.

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________

2) Twiggy and Sticky are moving boxes. Their boxes are the same weight, but Twiggy has an easier job than Sticky. Why?

A. Twiggy’s inclined plane makes the box smoother.
B. Twiggy is using a wedge. It helps her move the box to the table with less motion.
C. Twiggy is using an inclined plane. It helps her move the box to the table with less effort.
D. Twiggy’s wedge makes the box feel emptier.

3) Think about all the things in your house.

Name one thing that IS a simple machine: ________________________________

Name a SECOND thing that IS a simple machine: ________________________________

4) Give one example of a simple machine that makes pulling heavy things easier.

Simple machine: ________________________________

Explain how it makes pulling things easier:

___________________________________________________
___________________________________________________

5) Circle ALL of the objects that are wheel-and-axle systems.

Door Knob  Handlebar  CD  Jack-in-the-Box Handl

6) What simple machine is in the picture?

A. Inclined plane
B. Lever
C. Screw
D. Wedge

7) Think about all the things in your classroom.

Name one that IS designed by an engineer: ________________________________

Name one that is NOT designed by an engineer: ________________________________

8) The pictured gear train is used to

A. split things apart.
B. change the speed of spinning.
C. pull things to a higher height.
D. roll things across the floor.

9) Circle the object that is an example of a screw.

10) Think of a way pulleys are used in everyday life. First, DRAW how the pulley is used.

   Second, LABEL the pulley in your drawing.
11) Label *ALL* the simple machines you see on the picture of the bicycle below.

As an example of what to do, the brakes are labeled with an arrow as a lever.
Appendix E. Interview protocol.

Interview Protocol – Knowledge on Simple Machines

1. Have you heard of the term simple machines? What do you think of when you hear the words simple machines?
   a. Which of the following objects are simple machines?

   ![Simple Machines Images]

   b. Why did you pick those objects or parts of the object as a simple machine?
   c. What is the purpose of using simple machines? (If the kids say help us do work or moves things, then follow up with: OH, I see, What do you mean when you say work? How do simple machines help us do work?)

2. Can you describe for me the difference between a simple and a complex machine?
   a. What is the difference?
   b. Can you give me an example of a complex machine?

3. Twiggy and Sticky are moving boxes. Their boxes are the same weight, but Twiggy has an easier job than Sticky. Why do you think Twiggy’s job is easier?
   a. Depending on their answer a follow up question:
      i. Why does the plane (triangle) make Twiggy’s job easier?
      ii. Why does distance make Sticky’s job easier?
4. Here are two levers systems that have weights on them. Which lever would to lift the weight with the least amount of effort (i.e. force) when you push on the yellow part of the lever. Why that lever?
   a. Ok, lets test it. *Then give the students the lever with the fulcrum directly in the middle.* Ask them if they could think of a way to make it even easier to lift the weight? *IF the kids do not say move the fulcrum, first listen to what they say and then take the lever apart and give it to them again and ask them where they would put the fulcrum (or the black thing) to make it easier.* Why do you think moving the fulcrum there (left or right) would make it easier to lift the weight?
      i. *Kids might say shorter or longer, why shorter, why longer*
   b. Ok, so now lets test the other lever. Ask them where they would put the fulcrum (the black thing) to make it easiest to lift the weight. Why?

5. Give students a platform having different size gears on it.
   a. Ask the students which direction the big gear will spin if I spin the red clockwise (show the kids the direction the red gear will spin using the external red gear).
   b. Wait for a prediction. Then ask the kids. The red gear has 24 teeth, the great big gear has 40 teeth. Do you think the big gear will spin slower or faster than the red gear? Why? How much slower or faster?
   c. Before spinning the red gear, then ask which gear do you think will spin the fastest (the big one, the little, or the red one).
   d. Then spin red gear and ask the students to watch carefully what happens. If their predictions were wrong in questions 5a, 5b, 5c then ask follow up with probes about why, and if they predictions same thing, follow up with probes trying to better understand what they thought.
Appendix F. Rubric for the written pre- and post- test.

MULTIPLE CHOICE ITEMS:
Please record the letter that the student chose (A – D).
“E” for unanswered questions
“F” for illegible answers or multiple answers
If the answers are not lettered, but are four pictures horizontally:
the LEFTMOST item is A  B  C    the RIGHTMOST item is D

If the answers are not lettered, but are four pictures arranged in two rows, the choices will
be lettered as followed:
   A   B
   C   D

Ob3 - 2) Twiggy and Sticky are moving boxes. Their boxes are the same weight, but
Twiggy has an easier job than Sticky. Why?

A. Twiggy’s inclined plane makes the box smoother.
B. Twiggy is using a wedge. It helps her move the box to the table with less motion.
   C. Twiggy is using an inclined plane. It helps her move the box to the table with less effort.
   D. Twiggy’s wedge makes the box feel emptier.
Ob2 - 5) Circle **ALL** of the objects that are wheel-and-axle systems.

Door Knob  Handlebar  CD  Jack-in-the-Box Handle

Ob4 - 6) What simple machine is in the picture?

A. Inclined plane  
B. Lever  
C. Screw  
**D. Wedge**

Ob7 - 8) The pictured gear train is used to

A. split things apart.  
**B. change the speed of spinning.**  
C. pull things to a higher height.  
D. roll things across the floor.
Ob5 - 9) Circle the object that is an example of a screw.

[Image of a screwdriver and a tire]

OPEN RESPONSE ITEMS:

6: blank answer

7: I don’t know, I don’t understand

9: illegible

Ob1 - 1) Would it be easier to take the top off a paint can with a quarter or a screwdriver?

Circle one.

Quarter: [Image of a paint can with a quarter]

Screwdriver: [Image of a paint can with a screwdriver]

Explain why.

________________________________________________________________________________________

________________________________________________________________________________________

________________________________________________________________________________________
For a total of 2 points:

0: Irrelevant (quarter is metal), repeats question (easier to use quarter or screwdriver and says no more), circle and do not explain

1: Explanation discusses the merits of a screwdriver or a quarter that are not fully accurate, but have elements of the force-distance trade-off
~ discusses greater power or strength with a screwdriver
~ discusses edge of screwdriver (inclined planes or wedge at end) that helps to pry and stick further into the can edge
~ uses relative size of screwdriver/quarter to explain why would pick one, but only for the ease of holding the item

2: Discuss leverage or the force-distance tradeoff of using the lever or the quarter

Ob8 - 3) Think about all the things in your house.

Name one thing that IS a simple machine:_____________________________________
Name a SECOND thing that IS a simple machine:_________________________________

For a total of 2 points:
0: complex machines or non-machines
→ Can receive 1 point for each simple machine, for up to 2 points

Simple Machines: any objects that include only one simple machine: light switch, doorknob, window blinds, flag pole, stapler, knife, name of the simple machine that is also the name of the object (wedge, screw, pulley, gear, wheel and axle)
Not Simple Machines: any objects that include more than one or no simple machines/objects that do not help humans due to a force-distance trade-off: mechanical systems, electrical devices, cup, scissors, sink, floor, tile

**Ob10 - 4)** Give one example of a simple machine that makes pulling heavy things easier.

*Simple machine: ________________________________*

*Explain how it makes pulling things easier:*

________________________________________________________________________

________________________________________________________________________

For a total of 2 points:

0: list a complex machine or non-machine

1: list a pulley, inclined plane, wheel and axle, or gear as the simple machine that helps lift heavy things

2: provide an explanation that uses the simple machine listed to pull a heavy object

Simple Machines that make pulling heavy things easier: pulley, inclined plane, wheel and axle, gear

**ObEng - 7)** Think about all the things in your classroom.

*Name one that IS designed by an engineer: ________________________________*

*Name one that is NOT designed by an engineer: ________________________________*

For a total of 2 points:

0: not-relevant answers

→ Can receive 1 point for the engineered item and 1 point for the non-engineered item, for up to a total of 2 points
Engineered: object that was created or designed by an engineer, even if it was a long time ago; object that can be designed in many different ways (computer, water bottle, paper, bookshelf)

Not-engineered: living things (plants, animals, humans, air, water), thoughts, food, book (because considered to be designed/created by an author)

Ob6 - 10) *Think of a way pulleys are used in everyday life. First, DRAW how the pulley is used.*
*Second, LABEL the pulley in your drawing.*

For a total of 2 points:

0: No drawing, drawing does not include a pulley

1: Two methods to receive a one:
   ~ drawing includes pulley, but is not labeled or labels an incorrect part as a pulley
   ~ drawing includes a pulley, but not in a way that it would be used

2: Two methods to receive a two:
   ~ drawing includes a pulley in a way that it would be used AND is labeled
   ~ drawing includes a pulley in a way that it would be used
      AND an accurate explanation of its use

NOTE: Explaining, but not labeling the picture counts as labeling.

Ob9 - 11) *Label ALL the simple machines you see on the picture of the bicycle below. As an example of what to do, the brakes are labeled with an arrow as a lever.*
For a total of 2 points:

0: no simple machines labeled or no simple machines labeled accurately

0.5 point for each simple machine labeled accurately, for up to three simple machines or 3 points

List of simple machines in bicycle:

1. Levers: Brakes (which student cannot repeat) and lever to raise/lower bicycle seat
2. Wheel and Axle: BACK wheel of bicycle, pedals, wheel attached to pedals, handlebars, wheel-and-axle system to raise/lower bicycle seat (NOTE: if a student only labels with the word wheel, this is NOT accurate since a wheel by itself is NOT a simple machine)
3. Inclined Plane: NO inclined planes in bicycle so NO labeled inclined planes are accurate
4. Screw: Used as attachments at brakes near handle bars, where brakes meet wheels, connections between bars
5. Wedge: NO wedges in bicycle so NO labeled wedges are accurate
6. Pulley: Bicycle Chain
7. Gear: on back bicycle wheel any of the three parts towards the middle of the wheel
Appendix G. Rubric for the Interview protocol.

**Question 1**

<table>
<thead>
<tr>
<th>Score</th>
<th>Level</th>
<th>Description</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No Answer</td>
<td>Nothing is said.</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Wrong Answer</td>
<td>Response is wrong</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Unrelated Answer</td>
<td>Response is irrelevant to what is asked</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>Confused</td>
<td>The student recognizes that simple machines help, but hold a misunderstanding about how they help or what the purpose of using simple machines is.</td>
<td>- “Simple machines do some of the work for you”</td>
</tr>
<tr>
<td>2</td>
<td>Partial Understanding:</td>
<td>The student recognizes that simple machines help, but are unable to scientifically explain how they help (by changing the direction or the magnitude of force).</td>
<td>- “Simple machines help us do something (work)”</td>
</tr>
<tr>
<td>3</td>
<td>Complete Understanding:</td>
<td>The student understands that simple machines help by changing the direction of force or by reducing the amount of force. The student also recognizes that there is a trade-off between force and distance.</td>
<td>-</td>
</tr>
<tr>
<td>Score</td>
<td>Level</td>
<td>Description</td>
<td>Examples</td>
</tr>
<tr>
<td>-------</td>
<td>-------</td>
<td>-------------</td>
<td>----------</td>
</tr>
<tr>
<td>0</td>
<td>No Answer</td>
<td>Nothing is said</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Wrong Answer</td>
<td>Response is wrong</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Unrelated Answer</td>
<td>Response is irrelevant to what is asked</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>Confused Incomplete/Inaccurate/misconceptions</td>
<td>The student is aware that complex machines have multiple parts however, the student cannot clearly distinguish differences between simple and complex machines.</td>
<td>- “Complex machines work with electrical power”</td>
</tr>
<tr>
<td>2</td>
<td>Partial Understanding: Can distinguish the difference between complex and simple machines, but cannot go behind giving classical examples for complex machines.</td>
<td>Students recognize that complex machines include more than one simple machine in it, but are unable to identify if some machines are simple or a complex machine.</td>
<td>- The student thinks that scissors is a simple machine. - When complex machines are mentioned, the student thinks of cars, TVs, computers, etc.</td>
</tr>
<tr>
<td>3</td>
<td>Complete Understanding: The student demonstrates that he/she can distinguish all simple and complex machines.</td>
<td>The student understands that complex machines include more than one simple machine in it; thus this allows them to be able to do multiple tasks at the same time. The student can identify scissors, can openers, etc as complex machines.</td>
<td>-</td>
</tr>
</tbody>
</table>
### Question 3

<table>
<thead>
<tr>
<th>Score</th>
<th>Level</th>
<th>Description</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No Answer</td>
<td>Nothing is said</td>
<td>-Because there are less factors that are taken into account when force needs to be exerted.</td>
</tr>
<tr>
<td></td>
<td>Wrong Answer</td>
<td>Response is wrong</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Unrelated Answer</td>
<td>Response is irrelevant to what is asked</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Scientifically invalid explanations with good connected ideas</td>
<td>Scientifically invalid explanations (misconceptions) but good connections between ideas</td>
<td>-Because it increases at a lower angle and so you need to do less work to raise the block.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-Sticky’s job is easier because he needs to travel less.</td>
</tr>
<tr>
<td>2</td>
<td>Scientifically correct but incomplete explanations</td>
<td>Statements that provide incomplete explanations; usually missing one component of complete explanations.</td>
<td>-Even though it will take longer to lift the object, it will be a less painful lift.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Student does not see the connection between the simple machine reducing the force and increasing the distance.</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Scientifically correct and complete explanations</td>
<td>Statements that provide scientifically correct and complete explanations.</td>
<td>-B because it would require less force. However if the item was not very heavy I would chose plane A because it would require me to move to object less in distance.(18)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Student mentions that the inclined plane reduces the amount of force Twiggy applies even though Twiggy travels a further distance.</td>
<td></td>
</tr>
</tbody>
</table>
### Question 4

<table>
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</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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<td>Nothing is said</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Wrong Answer</td>
<td>Response is wrong</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Unrelated Answer</td>
<td>Response is irrelevant to what is asked</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>Confused</td>
<td>The student is aware that lever is a type of simple machine that helps humans do work. The student does not talk about the distance from the fulcrum (lever arm or load arm).</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Incomplete/Inaccurate/misconceptions</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Partial Understanding:</td>
<td>The student understands that levers are used to move objects by using less force and the longer the lever arm the lesser force is necessary to move it, but they are unable to completely explain the science behind it. The student cannot explain the relation between the load arm and the lever arm.</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>Complete Understanding:</td>
<td>The student understands that levers help humans by allowing them to use lesser force to move objects; the student also understands that there are trade-offs between force and distance, and force and time. Moreover, the student is aware that there can be different types of levers according to the purpose to use it.</td>
<td>-</td>
</tr>
</tbody>
</table>
## Question 5

<table>
<thead>
<tr>
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<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No Answer</td>
<td>Nothing is said</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Wrong Answer</td>
<td>Response is wrong</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Unrelated Answer</td>
<td>Response is irrelevant to what is asked</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>Confused</td>
<td>The student gets the direction and the speed</td>
<td>-The green turns faster because it is the</td>
</tr>
<tr>
<td></td>
<td>Incomplete/Inaccurate/misconceptions</td>
<td>wrong.</td>
<td>biggest (or there is more teeth on it).</td>
</tr>
<tr>
<td>2</td>
<td>Partial Understanding:</td>
<td>The student gets one of the two predictions</td>
<td>-The student is not aware that the number</td>
</tr>
<tr>
<td></td>
<td></td>
<td>right but with a wrong explanation.</td>
<td>of the teeth on the gears determines the</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>number of spins that the driven gear turns.</td>
</tr>
<tr>
<td>3</td>
<td>Complete Understanding:</td>
<td>The student gets both predictions right with</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>correct explanations.</td>
<td>-</td>
</tr>
</tbody>
</table>