EXPLORING MIDDLE-SCHOOL PROSPECTIVE TEACHERS’ CHALLENGES RELATED TO NEXT GENERATION SCIENCE STANDARDS

by

DONGMEI ZHANG

(Under the Direction of Barbara A. Crawford)

ABSTRACT

The dissertation consists of three related studies focused on how to support middle-school prospective science teachers prepare for the latest science education standards—Next Generation Science Standards [NGSS]. The first chapter provides an overview of the three studies. Chapters two, three, and four explore prospective middle-school teachers’ knowledge and beliefs about three new tasks proposed in NGSS. Specifically, in Chapter two, a case study conducted in a methods course is presented. This study aims to examine how middle-school prospective teachers’ knowledge about engineering design and its teaching changed during an engineering learning module. In Chapter three, a theoretical model about teaching crosscutting concepts is proposed using a cognitive perspective. An example is also presented to illustrate how to use the model to facilitate student learning of a set of crosscutting concepts from NGSS. In Chapter four, results from a multiple-case study are described. This study explored four middle-school prospective teachers’ beliefs, intentions, and practices related to the three-dimension teaching approach recommended by NGSS. The last chapter synthesizes the conclusions of the three studies, discusses the implications for science teacher education, and points out future directions.
INDEX WORDS: teacher education, science education, teacher knowledge, teacher beliefs, crosscutting concepts, engineering design, middle school
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DEDICATION

For my parents, Zhanjiang Zhang and Yuhua Wang, who always encourage and support me to improve myself; and for my dearest husband Xiaofu He, who provides me with love to achieve them.
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CHAPTER 1
INTRODUCTION AND LITERATURE REVIEW

With the release of the new K-12 Science Education Framework (NRC, 2012) and Next Generation Science Standards [NGSS] (2013), another round of science education reform declares its coming in the United States. The Framework and NGSS stem from the ideas of prior documents (e.g. AAAS, 1989; College Board, 2009; NRC, 1996), but they extend them in substantial ways (Reiser, 2013). Therefore, the new reform poses many challenges to the field of science education.

Although the implementation of a new science education reform is a systematic work involving many factors, the quality of teacher is always regarded as the most critical one (Bybee, 1993; Calderhead, 1996; Cuban, 1990; Levitt, 2002). After all, we cannot expect reform to be implemented successfully without qualified practitioners. In order to help teachers prepare for the new demands from the Framework and NGSS, efforts are needed to explore the challenges science teachers might face and the effective ways to cope with them.

Literature Review

There are three dimensions in the new K-12 Science Education Framework and NGSS: Practices, Crosscutting Concepts, and Disciplinary Core Ideas.

The Practices dimension of NGSS includes not only scientific inquiry, but also engineering design. In previous documents, scientific inquiry is regarded as the major way to teach science (NRC, 1996). In the NGSS greater emphasis is being put on the integration of
science, technology, engineering, and mathematics (STEM). The National Research Council (NRC) takes an “infusion” approach in incorporating engineering ideas into science classrooms (NRC, 2010). Specifically, the new reform combines engineering design with scientific inquiry to form the practice dimension of NGSS. The Engineering aspect is a good supplement to science education. Engineering design can benefit science learning, because it can not only provide children with relevant context to deepen their understandings about scientific knowledge, but also help them improve their abilities to solve authentic scientific problems. However, “there is not at present a critical mass of teachers qualified to deliver engineering instruction” (NRC, 2010, p. 1). To make things worse, “almost no undergraduate programs provide training for prospective teachers of engineering” (NRC, 2010, p. 17). Therefore, how to help science teachers develop their knowledge of engineering design and pedagogical insights of teaching design are significant issues that are worth being explored.

Crosscutting concepts are important themes that transcend disciplinary boundaries (AAAS, 1989). They “have value because they provide students with connections and intellectual tools that are related across the differing areas of disciplinary content (NRC, 2012, p. 218)”. Crosscutting Concepts are not new for science education. They evolve from the “common themes” in Science for All Americans (AAAS, 1989), the “unifying concepts and processes” in the National Science Education Standards (NRC, 1996), and the “unifying concepts” in Science: College Board Standards for College Success (College Board, 2009). Although the ideas of crosscutting concepts have been introduced to science education for a long time, they did not receive enough attention from researchers and educators (Kesidou & Roseman, 2002; NRC, 2012). In order to elevate the status of the Crosscutting Concepts, the new science education reform separates them from other components and highlights them as the second dimension of
NGSS. This means that the teaching and learning of crosscutting concepts are no longer a dispensable part of science instruction. Science teachers are encouraged to pay more attention to these concepts in their teaching practices and really think about how to use these important themes to facilitate students’ science learning progression.

Practices, Crosscutting Concepts, and Disciplinary Core Ideas are the three dimensions in the new Framework and NGSS. The reform emphasizes the significance of the three dimensions for science teaching and learning. Moreover, in order to reflect the interconnected nature of science, the reform requires teachers to teach science by integrating the three dimensions rather than introducing them in a separate way. However, integrating the three dimensions is a totally new task for science educators and there is even no adequate example to show how to do it (NRC, 2012). Furthermore, integrating the three dimensions coherently is challenging since teachers need to consider three aspects simultaneously and connect them logically. We cannot anticipate that teachers will be able to conquer this challenge in their teaching practice without any guidance or preparation. Therefore, how to support teachers in developing adequate knowledge and beliefs about the new three-dimension (3-D) teaching approach is an imperative issue faced by the field of science teacher education.

**Purpose of the Studies**

As aforementioned, the new U.S. NGSS reforms pose many challenges to science teachers. Teachers need support to help them shift from traditional ways of teaching to the new demands from NGSS. The purpose of this dissertation is to contribute insights to the field of new reform-based science teacher education. The overarching question is “how can science teacher educators support prospective middle-school teachers in understanding and navigating the new
challenges of NGSS?” Specifically, the dissertation focuses on three issues faced by science educators. These are (a) incorporating engineering design in science education, (b) teaching Crosscutting Concepts effectively, and (c) integrating the three dimensions in science instruction.

**Outline of Each Manuscript**

Chapter 2 explores how prospective teachers can be supported in developing knowledge about engineering design and its teaching; Chapter 3 establishes a model of teaching Crosscutting Concepts; and Chapter 4 examines how prospective teachers may learn about the three-dimension teaching (3-D teaching) and their belief development about the approach.

Chapter 2 aims to investigate strategies to develop prospective teachers’ knowledge about engineering design and its teaching in a methods course. It is a case study about 22 prospective middle-school teachers who participated in an “Engineering Design” learning model in a science methods course. The study scrutinizes how participants’ subject matter knowledge, learning insights, and pedagogical insights of engineering design develop in the three stages of the “Engineering Design” learning model. The results show that experiences in a methods course potentially can be effective for facilitating prospective middle-school teachers in developing their knowledge about engineering design and its teaching as long as the course is carefully designed. The implications of this study for science teacher education are also discussed.

Chapter 3 is a theoretical study focusing on how to teach crosscutting concepts effectively. First, it reviews the significance of crosscutting concepts for science education. Next, it defines the three levels of understanding crosscutting concepts from the cognitive perspective and discusses the relationship of the three levels. Then, it summarizes the principles of teaching crosscutting concepts by integrating the three-level understandings of crosscutting concepts,
learning theories, and requirements from NGSS. Based on the teaching principles, the study proposes a teaching model which could be used in K-12 science education to teach crosscutting concepts. To exemplify the use of the teaching model, the study also proposes how one might teach a set of crosscutting concepts ---system and system model in the context of physics. Finally, the significance and implications of this research are discussed.

Chapter 4 explores prospective teachers’ beliefs, intentions, and practices related to the “integrating three dimensions” teaching (3-D teaching) approach. The study uses a multiple-case study method to explore how four prospective middle-school teachers learned the three-dimension teaching approach in a methods course and begin their practicums during the same semester. The study creates profiles of each participant of the development of their beliefs about the three-dimension approach in a methods course; their intentions of using the new approach, and their enactment of this approach in their practicum settings. The results suggest that prospective middle-school teachers’ belief development about the three-dimension approach is a complex process involving many factors. Although prospective teachers realized the benefits of the three-dimension approach, they also worried about the difficulty of carrying it out in classrooms. Despite the intention of trying the new teaching method, no participant really used the three-dimension approach in their practicum, because their belief enactment is influenced not only by their beliefs about the three-dimension approach, but also by other beliefs in their belief systems and by contextual factors. The implications call for more supports from contexts, such as practicum schools and mentor teachers.

Chapter 5 connects the above three studies presented in Chapter 2-4 and provides a synthesis of the contributions of each study to better understand “what are effective ways to support prospective middle-school teachers in developing knowledge about engineering design
and its teaching, teaching crosscutting concepts, and learning the three-dimension teaching approach?” In addition, the implications for the field of science teacher education and future directions of this research are also discussed.
References


CHAPTER 2

PROSPECTIVE MIDDLE-SCHOOL TEACHERS’ KNOWLEDGE DEVELOPMENT OF ENGINEERING DESIGN AND ITS TEACHING

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1 Zhang, D. and B. A. Crawford. To be submitted to the Journal of Science Teacher Education.
Abstract

The new K-12 Science Education Framework (NRC, 2012) and Next Generation Science Standards [NGSS] (2013) emphasize students’ learning about engineering design in addition to science practices. How to help prospective teachers prepare for teaching in light of new reforms related to engineering is one of the imperative issues faced by science teacher educators in the United States. In this paper, we present a case study (Yin, 2014) that examined the development of twenty-two prospective middle-school teachers’ knowledge about engineering design and its teaching. Specifically, we designed an intervention named “Engineering Design” module for a science methods course and collected data from the three stages of the learning module. The data included participants’ pre-survey, team worksheet, two reflections, lesson plans, semi-structured interviews, and researcher field notes. Then, the inductive category development procedure (Mayring, 2000) was followed to analyze the data. This study suggests that experiences in a methods course potentially can be effective for facilitating prospective middle-school teachers in developing their knowledge about engineering design, ideas of learning design, and pedagogical insights of teaching design. The implications of this study for science teacher education are also discussed.

*Key words:* Engineering design, Teacher education, Teacher knowledge
Introduction

Nowadays, more and more emphasis is being put on the integration of science, technology, engineering, and mathematics (STEM) in teaching science in the United States. Although the idea of integrating engineering and technology with science has been proposed previously (e.g. AAAS, 1989; AAAS, 1993; NRC, 1996), engineering and technology have not received enough attention from science educators in schools (NGSS, 2013; NRC, 2009). In an effort to elevate the status of engineering and technology, and fully incorporate them into science instruction, the new K-12 Science Education Framework (NRC, 2012) and the latest science standards--Next Generation Science Standards [NGSS] (2013) highlight the core ideas of engineering and technology. Moreover, engineering design combined with scientific inquiry composes the first dimension--Practice dimension of NGSS.

Previously, the idea of design was regarded as part of technology education and called "technological design". In the new Framework and NGSS, design is assigned to engineering education and the term "technological design" is replaced with "engineering design". Engineering is different from technology, although they closely relate to each other. Engineering is "any engagement in a systematic practice of design to achieve solutions to particular human problems" (NRC, 2012, p. 11), whereas technology refers to the result of that systematic design practice (Achieve, 2013, Appendix I). Therefore, compared with “technological design”, “engineering design” lays more emphasis on the process of solving problems rather than the final resolutions or products. In this study, we utilize the definition of engineering in the new science education framework and use the term "engineering design" to refer to the iterative and systematic process for solving engineering problems by applying science (NRC, 2012).
Engineering has been described as "design under constraints" (Wulf, 1998). One of the underlying principles of these constraints is the laws of nature (NRC, 2010). Therefore, as the hallmark of engineering, design is not only the core idea of engineering, but also the natural link connecting science and engineering education. Moreover, engineering design can benefit science education by providing students with relevant questions to stimulate their interests to learn science, meaningful contexts to deepen their understandings about scientific knowledge, spontaneous opportunities to practice their experimental skills, and authentic problems to develop their scientific reasoning and analyzing abilities. Thus, the Framework claims, “it is the iterative cycle of design that offers the greatest potential for applying science knowledge in the classroom” (NRC, 2012, P. 201).

The new reform has posed a new challenge to the field of science education. How to facilitate the incorporation of engineering design in science classrooms is an imperative issue that needs to be addressed. Although education reform is a systematic work involving many factors, the quality of the teacher is always regarded as the most critical one (Bybee, 1993; Calderhead, 1996; Cuban, 1990; Levitt, 2002). After all, we cannot expect education reform to be implemented successfully without qualified practitioners. Therefore, in order to achieve the goals of engineering design set by the reform, science teachers need to master it first. However, "there is not at present a critical mass of teachers qualified to deliver engineering instruction" (NRC, 2010, p. 1). Teachers need help. To make things worse, “almost no undergraduate programs provide training for prospective teachers of engineering” (NRC, 2010 b, p. 17).

In this paper, we present a case study that aimed to explore effective ways to help prospective middle-school teachers develop their knowledge of engineering design and its
teaching in a university-based methods course. We will introduce prospective teachers’ learning processes at length and discuss strategies to promote their knowledge development.

**Theoretical Framework**

**Science Teacher Learning**

From a constructivist perspective (Richardson, 1997), teachers are not containers that hold knowledge and transmit it to students passively. Rather, teachers are learners who actively develop their knowledge and learn how to teach based on their own experiences (Feiman-Nemser, 1983). Therefore, experience plays an important role in teachers’ learning. Many researchers have studied teachers’ learning experiences and tried to identify the features of effective learning environments (e.g. Bellocchi et al., 2014; Binns & Popp, 2013; Birman, Desimone, Porter, & Garet, 2000). Although researchers take different perspectives and come to different conclusions, most of them agree that teachers should be given opportunities to experience the same learning that they expect of their students (Jeanpierre, Oberhauser, & Freeman, 2005; Lieberman, 1995; Loucks-Horsley et al., 1998). For instance, it is not realistic to expect a science teacher who has no inquiry experience to teach his or her students about how to use inquiry successfully, because it is “difficult if not impossible to teach in ways in which one has not learned” (Loucks-Horsley et al., 1998, p. 1). Likewise, science teachers need opportunity to go through the design process that they would like their students to experience, so they can get some sense of their future students’ thinking, predict possible problems occurring during design, and determine the difficulty of design activity properly (NRC, 2012; Pratt, 2013). If teachers lack similar experiences as those the science education reforms propose, then they will have to turn to
their previous learning experiences and revert to the teaching practices of their former science teachers (Kennedy, 1999).

Experience is the foundation of learning, including that of teachers. However, experience alone is not sufficient. In order to develop knowledge effectively, science teachers also need to reflect on their experience. Many researchers have studied teacher reflection, trying to find effective ways to facilitate it and using it to promote teachers’ learning (e.g. Carter, 1998; Danielowich, 2012; Gillies & Nichols, 2015; Hatton & Smith, 1995; Park & Heywood, 2012; Schon, 1987). For instance, Schon (1987) suggested that teachers need both reflection-in-action and reflection-on-action. The former refers to the reflection that occurs while teachers are teaching and the latter is the reflection occurring when teachers step back and retrospect their experience. Hatton and Smith (1995) found readings, oral interviews, writing tasks, and journals to be useful tools for promoting teacher reflection by giving them voice and making their implicit thoughts and assumptions explicit.

Although the idea of incorporating engineering into science education is not new, engineering education has been marginalized and did not receive adequate attention from the field of science teacher education (NRC, 2010). Consequently, only very few prospective teachers have the training experience to teach engineering (Katehi, Pearson, & Feder, 2009). Methods course can fill this gap by providing prospective teachers with the opportunity to engage in design activities and reflect on their design experience (Pratt, 2013). These will contribute to prospective teachers’ learning of Subject Matter Knowledge (SMK) and Pedagogical Content Knowledge (PCK) of engineering design greatly. For instance, personal design experience can give prospective teachers a solid foundation to comprehend the SMK of engineering design. Reflection-in-action helps prospective teachers understand the design
process that their students will go through more deeply. Although design activities contain SMK of engineering, prospective teachers may not be able to realize it. Reflecting on design practices can make the involved concepts and ideas more apparent. In addition, reflection-on-action can also help prospective teachers develop their insights about teaching engineering design by looking back on the difficulties they met and their feelings generated during design process.

**Science Teachers Knowledge**

Teacher knowledge is a major area of teacher education research (Abell & Lederman, 2007). Teacher education researchers has assumed various meanings to teacher knowledge and studied it from many perspectives since Shulman first proposed it (Abell, 2007). In 1986, Shulman defined teacher knowledge as the knowledge base for teaching and proposed a model to categorize it. After then, the model was refined and further developed by many researchers (e.g. Abell, 2008; Carlsen, 1999; Gess-Newsome & Carlson, 2013; Grossman, 1990; Magnusson, Krajcik, & Borko, 1999; Morine-Dershimer & Kent, 1999; Park & Oliver, 2008; Rollnick et al., 2008) to guide the research of teacher knowledge. Although researchers have different ideas about the details of the model, many of them agree that there are four types of teacher knowledge. They are teachers’ conception of subject matter knowledge (SMK), pedagogical knowledge (PK), pedagogical content knowledge (PCK), and knowledge of contexts (Kof C). In the field of science education, SMK refers to teachers’ knowledge about a certain science subject, including the syntactic and substantive knowledge of the scientific area. PK is science teachers’ general knowledge about instruction, including instructional principles, classroom management, students' learning, and educational aims. KofC refers to the knowledge about teaching environment, such as the situation of students, school, community, and district.
Proposed as the integration of the other three types of knowledge, PCK refers to the knowledge developed by science teachers to help them transform science knowledge to facilitate students’ effective learning (Carter, 1990; Geddis et al., 1993; Grossman, 1990; Marks, 1990; Shulman, 1987). PCK has five components. They are knowledge of (1) orientations towards teaching science, which means teachers’ comprehension of educational goals and general approaches to teaching science (Magnusson, Krajcik, & Borko, 1999); (2) students’ understanding in science, which refers to teachers’ knowledge of students’ conception and possible learning difficulties (Park & Oliver, 2008); (3) science curriculum, including the knowledge of available science curriculum, and related horizontal and vertical curricula for the science subject (Grossman 1990); (4) science instructional strategies, including activities, methods, and representations of teaching science (Magnusson et al. 1999); and (5) assessment of science learning, which refers to what knowledge should be assessed and how to assess it (Magnusson et al. 1999). PCK is the core of science teachers’ knowledge base and can influence science teaching practice directly.

Previously, research about science teacher knowledge mainly focused on science and science teaching (Gallagher, 1991; Crippen, 2012). With the inclusion of engineering design in the new reform, science teacher knowledge needs to be expanded to include the engineering aspect (NRC, 2012; Pratt, 2013). For instance, science teachers should comprehend the definition of engineering design and core ideas of engineering design listed in NGSS. In order to guide students’ design practice, science teachers need to know the characteristics of the design process and have some design strategies. In addition, as science teachers, they should understand the relationship between science and engineering. Besides the SMK of engineering design, science teachers also need to develop their PCK so that they can teach design effectively (Pratt, 2013).

For instance, science teachers need to know the possible difficulties that students may meet
during design process, the strategies that could be used to help students cope with learning
difficulties, the aspects that need to be considered when choosing design activities, and the
principles of assessing students’ learning from design experience.

**Overview of the Study**

This study was situated in a middle school science methods course in the 2014 spring
semester at a southeastern university in the USA. The goals of the course included helping
prospective teachers reinforce their knowledge of physical science and learn how to teach
physical science to middle school students. The class met three times a week and each class
session lasted 50 minutes. A total of 22 prospective teachers, including 18 undergraduates and 4
graduates, enrolled in the course. There were seven learning modules in the course and the two-
week-long “Engineering Design” was one of them. The first author was the instructor and
developer of the Engineering Design module. Before starting the module, instructors asked
prospective teachers to respond to a pre-survey about their previous engineering design
experiences and initial knowledge of engineering design and its teaching.

The “Engineering Design” module consisted of three stages. The first stage aimed to help
prospective teachers experience engineering design and acquire knowledge about it. In this stage,
prospective teachers spent three class sessions taking part in an engineering design competition
called “An Alarm System in Hospital” (Appendix B). The task was to design an alarm system for
one nurses’ office in a hospital. The system must be able to enable patients in two separate
patient rooms to call for help when they were in need of help. Specifically, when the patient in a
particular room pressed a button, the system should be able to alert the nurses of which of the
two rooms were calling for help. Designers could only use the given materials: batteries, buzzers,
switches, wires, bulbs, battery holders, and bulb holders. The price of each building component was listed in the instruction sheet. Before the competition, instructors divided prospective teachers into six teams by mixing their gender and learning levels. During the design process, teams recorded on a team worksheet, their trials by drawing circuit diagrams and the testing of their results of their circuits. After finishing the competition, the final designs were evaluated according to a quantitative rubric that consisted of four criteria: 1) achievement of function; 2) time consumed; 3) total cost of final product; and 4) the correctness of circuit diagrams. Prospective teachers were asked to submit a reflection on their own design experience.

The second stage was to give prospective teachers opportunity to share their design experience with their peers. During this stage, teams spent three classes working on their presentations, in turn, introducing their trials, demonstrating final products, and sharing their thoughts. Specifically, prospective teachers first introduced the circuits they tried, their test results for each trial, and the causes of failure, as they showed their records on their worksheets. Next, they demonstrated their circuits, reported the costs of their final circuits, and analyzed the pros and cons of their designs. Finally, they shared the difficulties they encountered during the design process, their solutions to the problems occurred, and their feelings about the design competition. During the presentations, other prospective teachers could ask any questions related to the design activity. Therefore, there were numerous opportunities for class discussions throughout the process of presentations. The first another made some field notes about the major points of the presentations and the class discussions occurred during the presentations.

The third stage focused on helping prospective teachers to practice and reflect on how to use a design activity to support physical science teaching. In this stage, prospective teachers were asked to create an individual lesson plan as their homework. The task was to teach a physical
science topic by using an engineering design activity. Prospective teachers were also asked to reflect on their lesson planning by writing the second reflection. About two weeks later, researchers employed maximum variation sampling methods (Patton, 2002) to select ten prospective teachers to conduct semi-structured interviews. Researchers aimed to explore participants’ learning experiences in this engineering design module and gather their perceptions of engineering design and its teaching.

We asked the following research question: In what ways, if at all, did prospective middle-school teachers’ knowledge about engineering design and its teaching change during this university-based learning module?

Methods

This is a case study (Yin, 2014) of a group of middle level prospective teachers in a methods class. The purpose of the study was to explore in depth prospective middle-school teachers' knowledge development of engineering design and its teaching in a university-based methods course. The twenty-two prospective teachers enrolled in the class were the participants of this study.

The data in this study included a participant pre-survey, team worksheet, two written reflections, lesson plans, semi-structured interviews, and researcher field notes. The pre-survey examined participants’ prior design experiences and probed their initial knowledge of engineering design and its teaching. The first written reflection demonstrated what knowledge of engineering design and its learning participants gained from the first stage of learning. The team worksheet showed participants’ design process and this was used as a reference when analyzing the first reflection. The researcher’s field notes recorded the major points of the team
presentations and participants and teacher’s class discussions, which gave information about how participants’ knowledge of engineering design and its learning were further developed in the second stage of learning. Participant lesson plans and the second written reflection revealed what pedagogical insights that participants gained in the last stage of learning. The interviews gave more in-depth insights into participants’ knowledge development process during the whole engineering design learning module.

All ten interviews were transcribed. Researchers analyzed participants’ responses to the pre-survey by registering their prior design experiences and evaluating their initial knowledge of engineering design and its teaching. Specifically, participants’ prior design experiences were classified as engineering design experience or non-engineering design experience based on their self-reports and whether the goal of their design activity was to “achieve solutions to particular human problems”. For instance, although Paul identified “leverage and pulley experiments” as one of his prior engineering design experiences, researchers classified it as non-engineering design experience since its goal was to explore how leverage and pulley work rather than using them to solve problems. Researchers also examined participants’ initial knowledge of engineering design and its teaching. Responses like “Use formulas”, “Drawing & Sketching”, and “Measurement” were not counted as knowledge of engineering design since they are not the unique ideas of engineering. Ideas, such as “Functionality”, “Draft of solution”, and “Test model” were classified as knowledge of engineering design because they relate to the concepts or core ideas of engineering design. The general teaching strategies, like “Understand vocabulary words”, “Start from basic and build up from there”, and “Follow directions” were not counted as knowledge of teaching engineering design. Responses like “Help student see the problem first” and “Student need creativity to design models” were regarded as the knowledge of teaching
design since they were insights of promoting design learning. In addition, participants’ initial knowledge of engineering design and its teaching were determined to be one of the following levels: N (None), L (Little), S (Some), and M (Multiple) levels. N level had no thoughts; L level had 1 or 2; S level had 3 or 4, M level had 5 or more ideas. The ten interviewees were selected based on the levels of their initial knowledge of engineering design and its teaching (See appendix F).

Researchers analyzed written reflections, lesson plans, semi-structured interview, and researcher field notes by taking the inductive content analysis (Mayring, 2000) approach because science teachers’ learning of engineering design is a new topic for the field of science teacher education and the inductive approach allows “the categories and names for categories to flow from the data” (Hsieh & Shannon, 2005, p. 1279). More specifically, first, researchers scrutinized participants’ knowledge of engineering design developed from the first two learning stages by analyzing first reflection, interview transcripts, and field notes. The team worksheet was used to help make references. For instance, “Make circuits as cheap as possible” was coded as “Low Cost”; “Finish the circuits as soon as possible” was code as “Short Time”; “Make sure our circuits actually work” was coded as “Good Function”. All of these codes were grouped to the category “Criteria of the design problem”. “What materials we can use” was coded as “Given Material” and belonged to the category “Constraints of design”. The two categories “Criteria of the design problem” and “Constraints of design” were then collapsed to the theme “Define and delimit problems”. Next, researchers reanalyzed the first reflection, interview transcripts, and field notes to examine participants’ insights of learning design. The team worksheet was again used as reference. For instance, “The tradeoff practices critical thinking” was categorized as “Critical Thinking”. “We have to logically think about many aspects of
design.” was categorized as “Logical Thinking”. The two categories were collapsed to the theme “Engineering design involves high level thinking”. Finally, researchers examined the pedagogical insights of teaching engineering design which emerged from participants’ lesson plans, the second reflection, and interview transcripts. For instance, “It took a lot of trial and error” and “We were able to cut out a wire by joining the bulb-holders” were categorized as “Modification”. “If the design did not work as planned, we would draw another and create that” and “We tried again with another idea” were categorized as “Redesign”. The categories “Modification” and “Redesign” were collapsed to the theme “Students need to modify or redesign multiple times”. Another example is, “I would walk around the classroom observing students” was categorized as “Observation”; “During the design process, I will ask students questions” was categorized as “Questioning”; “Students will also work on a questionnaire to see what they have learned” was categorized as “Questionnaire”. The three categories “Observation”, “Questioning”, and “Questionnaire” were collapsed to the theme “Use formative assessments”.

Given that “the researcher is the instrument” for qualitative research (Patton, 2002), the instructor status of the first author helped to develop a holistic and deep understanding about this case study. However, on the other hand, the insider status may have also brought bias to this study. Therefore, in order to reduce the possible skewing of data analysis and interpretation, the first and second author analyzed the data together and discussed disagreements that occurred during the analysis process.

**Results**

In this section the authors will present the main findings. Data analysis of the pre-survey showed that although all participants had some kinds of design experiences (e.g. art design,
website design, interior design, clothing design), their prior engineering design experiences were deemed to be insufficient overall. Among twenty-two participants, ten had no engineering design experiences, ten had only one, and two had only two related previous experiences. The four graduate students had no more engineering design experience than the undergraduates. Participants’ prior engineering design experiences included: building bridge, designing Rube Goldberg machine, building tower; making paper airplane, building egg holder, designing mouse trap car, making rocket, and creating a roller coaster. Because of insufficient prior experiences, participants’ initial knowledge of engineering design and its teaching were very limited. Among twenty-two participants, three had “None” and nineteen had “Little” knowledge of engineering design; seventeen had “None” and five had “Little” knowledge about teaching engineering design. In fact, participants’ initial knowledge of engineering design and its teaching were not only insufficient, but also stereotyped or even incorrect. For instance, Olga’s understanding of engineering design was very narrow. She wrote that engineering design was “to make something that functions or runs by an engine or something like an engine”. Gale confused engineering with science and said that “the center of mass” was one of the examples of engineering design. When talking about teaching engineering design, Yetta believed engineering design was a “mirror scientific method” and teachers should help students “formulate a hypothesis” during design process. Nina thought that engineering design could only be taught in physics units.
<table>
<thead>
<tr>
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<th>Design</th>
<th>Engineering Design</th>
<th>Learning</th>
<th>Prospective Teacher's Knowledge of Engineering Design and Its Importance</th>
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Table 2.1
Stage 1: Circuits Design Experience

There was evidence that participants’ circuits design experiences in class contributed to their knowledge development of engineering design and its learning. Specifically, the circuits design activity provided participants with opportunity to engage in engineering design, in person. Based on their personal design experience, participants developed their knowledge of engineering design and gained insights about the possible difficulties for learners (Table 2.1).

Knowledge of Engineering Design

There is evidence that participants’ knowledge of engineering design was enhanced by engaging in the circuits design activity. Specifically, participants expanded their definition of engineering design, developed some understandings about the core ideas proposed by NGSS, acquired designing strategies, and made clear the relationship between science and engineering.

When reflecting on their circuits design process, all twenty-two participants (100%) mentioned the first two core ideas of engineering design. Specifically, when relating the design problems they faced, participants mentioned how they planned their designs by considering all involved constraints and criteria. Just as Bess wrote “we had to think about how function, how cheap, and how quickly we were able to get our design done” (Bess, Reflection #1). Sonia also mentioned “we had to keep in mind budgeting, time, materials provided, efficiency, and real world practically” (Sonia, Reflection #1). When stating the process they tried possible solutions, participants emphasized they had to keep on building and testing circuits model until they got a workable design. For instance, Paul described his design process as “Design the diagram. Make the circuits. Doesn’t work. Then, design a new one and make a new circuit. Again, again and again” (Paul, Reflection #1). Ella also wrote “trial and error was very much included in the
design process. We kept testing the designs that we came up with and if they did not work, we tried again with another idea” (Ella, Reflection #1).

All participants (100%) expressed the realization that science is the necessary foundation for engineering design, since engineering design applies science knowledge. For instance, Tess wrote, “I would not have known how to do anything today without background knowledge on circuits and Ohm’s law” (Tess, Reflection #1). Ada also mentioned “I didn’t know engineer involves science. I just thought it is all about math. Nobody tells me that there is close relationship between science and engineering design. The circuit design project definitely helped me realize that” (Ada, Interview, April 16, 2014).

Thirteen participants (59%) developed their understandings of the third core ideas of engineering design proposed by NGSS. For instance, participants reflected on how they optimized their designs by striking a balance between criteria so that they could get their best solutions. Ziv mentioned “we were considering design foremost, but once we understood how to set up the circuit correctly, we took out any unnecessary parts to lower the cost” (Ziv, Reflection #1). Gale wrote that their team tried to “find a way to reduce cost without losing functionality” after they got a workable circuits model (Gale, Reflection #1).

Thirteen participants (59%) recognized that engineering design is the bridge that connects science knowledge with real world problems. For instance, Rita wrote “building circuits, for me, allows me to apply my book knowledge to real world circumstances” (Rita, Reflection #1). Ada said,

Physics has always been pretty abstract to me. I always knew it was useful to learn, but I didn’t think of it as being used in the real world. It was too math intensive. After the
design process, I now see that it goes beyond just equations on paper (Ada, Interview, April 16, 2014).

A total of five participants’ (23%) enhanced their comprehension of engineering design. They realized that their previous understanding of engineering design was narrow. Engineering design was not limited to some types of machines. Any designs which aim to meet peoples’ needs could be regarded as engineering design. Therefore, there are many diverse engineering designs and engineering design is everywhere in our daily lives. For instance,

I didn’t really know engineering design before we did it [circuits design]. The only thing that I thought of engineering design is robots. That is all I thought about it. I didn’t really know what else you could do for engineering. But, once we did the whole circuits, I understood that you could do many different things. (Olga, Interview, April 17, 2014)

At first, I didn’t know anything about engineering. I didn’t make connections with my daily life. But after the project, I was like, oh, there are a lot of examples around us about engineering. For instance, like this table. It has to have enough supporting force when I put something on it, it doesn’t fall through. The chair, the same thing. The mug that I bring with me to the class every day. It keeps heat really well. I mean, after our project, I started to notice the engineering aspect around my life. Engineering goes into everything around us. (Ada, Interview, April 6, 2014)

Four participants (18%) acquired some strategies that could help them diagnose design problems. Specifically, participants learned when something was wrong with design, they could pinpoint problems by using a decomposing strategy to test each part of the circuits. This strategy could help designers improve efficiency by avoiding unnecessary redesigning. For instance,

When you have a system, you check this part first to see if it works. Then, you check that
part. It will help you to find out what’s wrong with your design rather than I have this design, let’s make a whole new design. (Olga, Interview, April 17, 2014)

After making sure that every part worked well, designers could get a possible solution by using a combination strategy. Just as Hebe wrote,

We went first to figure out the circuit as a whole, but when we couldn’t complete it or figure it out this way, we then, individually, took piece by piece (or room by room) to figure the circuit this way. Then, we tried to figure out a way to connect all the parts. (Hebe, Reflection #1)

Designers could also employ accumulation strategy by keeping the workable parts and modifying the problematic ones. For example, Ziv wrote that “we used the part that worked well and changed the part that didn’t work. We repeat this process until we get our final design” (Ziv, Reflection #1). Hebe mentioned “we had mainly trial and error over and over again to figure out what aspects of our circuit worked and then trying to get the successful parts into a whole” (Hebe, Reflection #1).

**Knowledge of Learning Engineering Design**

The data analysis of participants’ first written reflection showed that, besides the knowledge of engineering design, participants’ personal engineering design experience also helped them identify the possible learning difficulties, foresee students’ feelings generated during design process, and find effective ways to facilitate design learning.

Participants learned that engineering design was not an easy task and many difficulties were associated with its learning process. First, all participants (100%) redesigning might be needed. Generally, designers could not achieve the goal of design on their first try. If a designer
cannot pinpoint and solve the problems, they need to rethink and redo their designs. This ability to pinpoint problems was especially difficult for learners when they thought their designs were already theoretically perfect. For instance, Ada wrote “Our first try theoretically should have worked, so after that, it was a little hard to find another way” (Ada, Reflection #1). Second, eleven participants (50%) thought that lots of decision-making is involved when optimizing designs. Even after designers get a workable solution, they still need to optimize their designs. Lots of decision-making is involved when designers make tradeoffs and try to strike a balance between all criteria. For instance, Sonia mentioned that her design team had a hard time weighing “whether or not we should focus on cost/time efficiency or real world application” and “we were so afraid to lose points with time and cost that we sacrificed practicality” (Sonia, Reflection #1). Third, ten participants (45%) learned that engineering design requires the ability to solve practical problems. Many unexpected problems may likely occur during the design process. In order to come up with a workable product, designers need to be able to solve all encountered problems. How to solve these practical problems by applying their science knowledge was hard for learners. For instance, Paul used the word “unpredictable” to describe various problems occurred in his circuits design experience. Tess wrote “Once we made a circuit, we had to determine what went wrong. Sometimes it was because the resistance was too high and other times it was because there was an error in the wiring” (Tess, Reflection #1). Fourth, eight participants (36%) learned that engineering design requires creativity. In order to solve design problems, designers needed to use creativity to create their own products, rather than following existing procedures. Ella wrote, “I had to think creatively to create the circuit design and I had to think creatively to come up with my own design” (Ella, Reflection #1). This creativity requirement might be challenging for the learners who were used to passive learning.
Fifth, eight participants (36%) thought that engineering design involves higher level thinking. Engineering design achieves its goal under some constraints. The designer needs to critically consider all involved criteria and constrains, and use logic when planning a design that has possible solutions. For instance, Olga wrote “it was not easy. Building a circuit is a very detailed process because so many things go into making it work” (Olga, Reflection #1). Ziv stated he, “has to not only get the project right, but need to consider time and cost” (Ziv, Reflection #1).

A total of twelve participants (55%) expressed negative feelings associated with the iterative design process. They used the word “frustrating” to describe their feelings during the circuits design process. Specifically, participants’ frustration started when their first trial did not work. Just as Ziv wrote “The difficult part was our first design didn’t work. It was frustrating to solve with” (Ziv, Reflection #1); participants felt frustrated when their theoretically correct designs failed in reality. Just as Iris mentioned “we had a ‘dream’ circuit in mind but not being able to accomplish. It was a little frustrating” (Iris, Reflection #1); participants became frustrated when they knew there was something wrong with the circuits, but they could not pinpoint the problems. For instance, Tess wrote “I got frustrated at times because I thought we were doing everything wrong” (Tess, Reflection #1); participants experienced frustration when they knew what the problem was, but they could not solve it. Just as Iris wrote “when we couldn’t figure out how to get both light bulbs to work with the buzzer, it got a little frustrating” (Iris, Reflection #1); participants felt frustrated when they were stuck in the problems for a while. Hebe wrote “for me, this was frustrating because it took a long time to solve for us” (Hebe, Reflection #1).

Based on their own circuits design experiences, eleven participants (50%) learned that teamwork could facilitate both design and leaning process. Engineering design was not easy and many challenges resided in the iterative design process. In order to achieve the goal of design,
team members needed to collaborate with each other by communicating, discussing, and negotiating their ideas. For instance, Bess wrote “it is helpful to have a group to do this with so you can have other people to bounce ideas off” (Bess, Reflection #1). Olga also wrote, “since I worked with two other people, we collaborated in order to find the best design for our team” (Olga, Reflection #1). In addition, teamwork could not only promote design, but also help learning. When some learners lost their way in the design process, they could catch up by watching or talking with their team members. Just as Ward mentioned, “If one person in the group has no idea about the design, the group may still do well. But, that one person still might be a little confused. They understand it when they see someone do it” (Ward, Interview, April 16, 2014).

**Stage 2: Team Presentation and Class Discussion**

During the second stage of the learning module, participants’ knowledge of engineering design and its learning were further developed by presenting their final solutions, sharing their design processes, communicating their thoughts, and discussing ideas in class (Table 2.1).

*Knowledge of Engineering Design*

There is evidence participants learned about the characteristics of engineering design. For instance, all participants’ (100%) understanding about the iterative process of design was developed. Participants’ personal design experience helped them realize the design process might not be straightforward. The team presentations strengthened this point. The team worksheets indicated that, before getting the final designs teams tried various ways to solve the problem. For example, one team tried 2 different circuit models, four teams tried 3, and one team tried 5
(Figure 2.1). Three teams mentioned explicitly that they tried more models than they actually recorded on the worksheets. By observing the different designs of other teams, all participants (100%) learned that, unlike science problems, one design task might have many possible solutions. For instance, Ziv mentioned that “there are many possible designs for the same design problem just as different teams came up with different solutions when we did the circuit design projects” (Ziv, Interview, March 25, 2014). All participants (100%) learned that every design had its pros and cons because designers weighed criteria differently. For instance, Paul’s team used a bulb and buzzer for both rooms. Paul’s team’s design could function well by alerting the nurse via both light and sound. But, their circuits cost much more money than other teams’ designs. On the contrary, Demi’s team’s design used only one buzzer for the two rooms, to reduce the cost of the circuits. However, their circuits could not distinguish which rooms were calling for help.
<table>
<thead>
<tr>
<th>Circuits</th>
<th>Circuit Diagrams with Symbols</th>
<th>Test Results &amp; Problems</th>
</tr>
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<tbody>
<tr>
<td><strong>First Try</strong></td>
<td><img src="image" alt="Circuit Diagram" /></td>
<td>Buzzer went off but no light (might be too dim)</td>
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<tr>
<td><strong>Second Try</strong></td>
<td><img src="image" alt="Circuit Diagram" /></td>
<td>(added more batteries) Still not working...</td>
</tr>
<tr>
<td><strong>Third Try</strong></td>
<td><img src="image" alt="Circuit Diagram" /></td>
<td>Both bulb light but buzzer won’t stop</td>
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<tr>
<td></td>
<td><img src="image" alt="Circuit Diagram" /></td>
<td>Buzzer didn’t work</td>
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<td></td>
<td><img src="image" alt="Circuit Diagram" /></td>
<td>cost too much</td>
</tr>
<tr>
<td></td>
<td><img src="image" alt="Circuit Diagram" /></td>
<td>save two wires Final!</td>
</tr>
</tbody>
</table>

Figure 2.1: Team worksheet from one design group


Knowledge of Learning Engineering Design

Nine participants (41%) realized that science inquiry could be used to pinpoint design problems. Specifically, when talking about the difficulties they encountered in design, four teams mentioned the same issue related to the physics. That is, when building parallel circuits with one bulb and one buzzer, only the bulb worked. Participants discussed the possible causes by using their knowledge about circuits. Some participants speculated that it was because the battery was old and its voltage was not high enough to make the two items work together. Other participants inferred that it was because the resistance of the buzzer was much higher than the bulb. This made the electric current going through the buzzer too low to make it work. When instructors asked participants how they determined which hypothesis was correct, participants said they could do inquiry by changing batteries or measuring resistance.

When sharing their feelings during the team presentation, participants argued about the competition aspect of the circuits design activity. Some participants (27%) said they enjoyed the competition format because it made the design activity like a real world problem, added fun to learning, and gave designers more motivation. For instance, Ziv said “the time constraints made the activity real. In real world, you have to come up with good designs as fast as you can. Consumers will not consider your design if you spend much more time than others” (Ziv, Field Notes). Ada mentioned, “making it a competition made us really interested in doing our best and showing the class how good we were at making circuits” (Ada, Field Notes). However, other participants (27%) disagreed and said that competition aspect was not appropriate for class design activity. First, competition brought pressure to designers and distracted their concentration. Just as Yetta said,
The competition put stress on me and took away from the main purpose of the assignment which is to think critically as well as implement science inquiry. Because I was so worried about getting last, I felt like I could not clearly approach the design.

(Yetta, Field Notes)

Second, it was not good to ask classmates to compete with each other. Kate said that “competition is not good in a classroom, it is important to work together and not bring one another down” (Kate, Field Notes). Third, designers should be given enough time to experience the iterative design process. Sonia said that their team was afraid of losing points for finishing last. So, they worked fast without considering many possibilities. After a heated discussion, participants reached a consensus. That is, the teams agreed it was best to use healthy competition for this class design activity.
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<td><strong>Enhance students through design process</strong></td>
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Stage 3: Lesson Planning

Based on the knowledge gained in the first two stages, there is evidence participants developed some insights about how to teach engineering design during the lesson planning stage (Table 2.2). Specifically, participants knew what difficulties students might meet in design, proposed strategies that could facilitate design learning, indicated their orientation of teaching design, gave suggestions for curriculum, and stated their principles of evaluating design learning.

Knowledge about Learners

Based on their own circuits design experience, participants anticipated their future students would meet the following challenges in their design learning. First, ten participants (45%) thought it was almost impossible for students to achieve designs on their first try. Students needed to modify, test, and rethink their designs multiple times before they could get a workable product. For instance, Iris wrote that students “may need to rethink their plan, add materials, or start over again” in her lesson plan. Second, six participants (27%) thought students might have little prior experience of engineering design just like these prospective teachers themselves. Third, six participants (27%) thought the countless trials, problems, mistakes, failures associated with the iterative design process would influence students’ moods negatively and make them feel frustrated. Just as Olga said, “if students are not able to make the circuit work, they may feel frustrated, like what I experienced…If they do many many trials, they will also get frustrated” (Olga, Interview, April 17, 2014). Fourth, many unexpected practical problems could occur in the design process. Four participants (18%) anticipated that students might be stuck or lost in design if they had no clue about how to deal with problems or failed to solve them, just as Kate wrote in her lesson plan. Fifth, engineering design requires students to design creatively. This is different
from traditional class activities, which generally have detailed procedures to follow. Therefore, three participants thought students may feel it is difficult to complete the design task. For instance, Nina said, “It might be that some groups even cannot come up with a complete design product” (Nina, Interview, April 19, 2014). Sixth, three participants thought that students must use higher level thinking to critically and logically consider all criteria and constraints of design problems. This is not easy for middle school students. For instance, Kate wrote, “They [students] have to critically think about many aspects of the assignment to complete it correctly” (Kate, Reflection #2). Finally, in order to get the best products, students needed to optimize their designs by making tradeoffs among all criteria. Two participants thought that it was difficult for students to make decisions when they faced many choices. Just as Ward mentioned in his lesson plan, “some students may have a hard time weighing the tradeoffs, like getting full points on the design but getting half the points on cost”.

Orientation of Teaching

Participants stated that this design activity should give students ownership of science learning. First, five participants (23%) thought teachers should give students the freedom to design their own products, rather than let them just follow some given instructions. For instance, Ward stated, “Putting the learning actually in students’ hands and letting them physically move stuff around and build something. And, then seeing how it related to science” (Ward, Interview, April 16, 2014). Second, four participants (18%) thought, when students had to work out puzzles, teachers should give students the chance to find the answer via their own inquiry. Bess wrote, “design activities should allow students the opportunity to struggle with concepts and explore them” (Bess, Reflection #2). Third, three participants (14%) thought, when students encountered
problems, teachers should give students time to think about it and come up with their own solutions instead of helping them immediately. For instance, Hebe wrote, "For the first half [class], the students have to go about everything on their own. I won’t answer any questions and they have to try to solve it on their own” (Hebe, Lesson plan).

Teaching Strategy

Engineering design is not easy and there are many difficulties associated with its learning process. Therefore, eleven participants (50%) believed teachers should help students go through the design process, so they would not get stuck or lose sight of the design. Assistance from teachers could include, using scaffolding questions, giving hints, or giving more guidance. For instance, Iris designed scaffolding questions for students in her lesson plans. Kate explained “I plan to give hints to help them move along without giving them the full answer” (Kate, Lesson plans). In interview, Olga said, when students were stuck in design, she would guide students by talking with them and seeing what the problem was. In addition, participants believed teachers could reduce their supports gradually after students were used to design activity. For instance, Yetta wrote,

In the beginning, I would really help them do it and scaffold them. And then, as a year progresses, I would take that off and see how they can improve on their own. Hopefully, by the end of the year, I will be able to give them materials and directions, and have them create engineering on their own. (Yetta, Reflection #2)

Teamwork is an important aspect of engineering design. Eleven Participants (50%) thought teachers should group students properly by mixing their levels and work ethic. This would help with class management, facilitate the design process, and promote learning. For
instance, in her lesson plan, Kate explained, she “wants the teams to be balanced so that those who may struggle are with students who can help them to understand when I may be busy with another group”. Jane also said,

Students are very different in terms of their work ethic, concentration, and caring level. So, I would really want to make sure that the distribution of that was even. I have at least someone on each team. I think, ok, they would be really good motivators. (Jane, Interview, March 21, 2014)

Moreover, nine participants (41%) thought teachers should emphasize the collaboration of team members explicitly in class, such as students should be open to and respect other’s ideas. For instance, in her lesson plan, Demi wrote, “student will be reminded that they are to respect their classmates and themselves when talking to one another”. Jane also mentioned “they [students] need to learn to listen to each other in order to better communicate with their peers” (Jane, Interview, March 21, 2014).

Participants thought that after students finished the design activity, teachers could use team presentations, class discussions, and reflection to promote students’ learning. Specifically, seven participants (32%) thought students could see different designs by doing presentations. This would give students different perspectives of design and expand their minds. Nine participants (41%) thought, conducting a class discussion during presentations would give students opportunities to discuss their problems and defend and argue for their solutions. Teachers could also take advantage of it to deepen students’ understanding by asking questions. For instance, Ziv gave the following explanation about why he arranged the presentation and discussion procedures in his “Designing Boat” lesson plan.
Each group would present because this could be an “uh-huh” moment for another group. You know, “ha, we should have done that”. You take that as an instruction moment too because everybody looks at everybody’s boat in the classroom. I think that is something that we definitely do at the end of engineering design activity. You could also ask questions about it. (Ziv, Interview, March 25, 2014)

Thirteen participants (59%) thought teachers could help students make the involved design concepts and principles clear by asking students to reflect on their design learning experience. Just as Ward said,

They were doing the practices of engineering design and they don’t realize the knowledge embodied in it …When they go back and say “ok, this aspect working with time constraints, this is the tradeoff between time and function”. I mean, after they go back, they will feel like “ok, I see that now”. (Ward, Interview, April 16, 2014)

Given that competition could bring students both motivation and pressure, six participants (27%) thought teachers should use healthy competition in design activity. Specifically, instead of competing with other teams, teachers could ask students to compete with given time. For instance, Ward asked students to “race against the clock” in his lesson plan. As long as teams could finish design within given time, they get full points for the time criteria. Or, ensure that the incentive for the “win” team was not too much. Just as Jane said, “Having a little bit of rival between students [is good] as long as it is healthy. Not too much to make them fight. But, enough to get them really motivate to work. I think it is a good motivator” (Jane, Interview, March 21, 2014).

Participants thought that teachers should help students with some preparation before actually letting them carry out the actual engineering design project. Specifically, science
knowledge is the foundation for engineering design. Five participants (23%) thought teachers could help students prepare for design activity by reviewing related science topic first. In addition, considering that students may have little, or even no prior engineering design experience, four participants (18%) thought teachers should give students necessary instruction about engineering design first, such as what is engineering design and some general strategies to do it. These strategies might help facilitate students’ design process. Just as Rita stated, “I feel that students need an appropriate amount of instruction and knowledge gain prior to any engineering design projects. Going into it blindly with students will cause lots of confusion and frustration” (Rita, Reflection #2).

Three participants (14%) thought teachers could help students reduce their frustration associated with design by using two strategies. First, teachers could help students make mental preparation by telling them the iterative features of design process explicitly. For instance, Olga said,

For a college student, it was totally understandable that it [design process] wasn’t straight forward. It shouldn’t have been straight forward. But, I probably would make it a little more clear about what I want them [students] to do because with 8th grade students, I think they would have struggled if it was vague (Olga, Interview, April 17, 2014).

Second, three participants (14%) teachers should keep on encouraging students during the design process. For instance, Nina said, “I think if you can tell your students to persevere and continue the process. It would be less frustrating and they will eventually understand” (Nina, Interview, April 19, 2014). Olga also said “I will encourage my students, and say ‘it is ok to make mistake. That is how you learn’ (Olga, Interview, April 17, 2014).
Knowledge about Curriculum

Thirteen participants (59%) thought it was better to use the design activity coming from the real-world problem. This would help students see the connection between science and the real world, realize the significance of scientific knowledge as a citizen, and improve students’ interests in science learning. In order to identify the real-world design activities, teachers could select design topics from real-world problems. For instance, Paul asked students to design a solar cooker to reheat pizza in his lesson plan. Or, teachers could modify the original activity to make it more like a real-world problem by incorporating the concepts of engineering design. For instance, Carol added the cost constraints to her “Building with Pasta” activity. She gave the following explanation:

The limit on how much they [students] can spend makes it more “real life” for them. No one has unlimited funds, and engineers have to make the most out of the money they have to spend… Engineers have to do this, and I want this activity to be as real life as possible. (Carol, Lesson plan)

The design process is not straightforward. Usually, students need to modify, test, and rethink their designs multiple times before getting their final solutions. Nine participants (41%) thought teachers could use worksheets to help students record their tries, testing results, problems, puzzles, and solutions. This would help students recall and reflect on their design process.

The iterative design process contains the core ideas of engineering design. The problem solving associated with the design process could help students deepen their understanding of science concepts and improve their abilities of applying science knowledge. Therefore, eight participants (36%) thought teachers should give students enough time to do design practice. Just
as Liz wrote in her lesson plan, “they [students] will be given ample time to construct and test their bobsled, make any necessary changes”. In fact, most participants’ lesson plans took several classes, instead of one class, because they wanted to give students enough time to experience the modification and optimization of design.

Engineering design needs to use science knowledge. Therefore, seven participants (32%) thought the design activity should be sequenced after teaching a related science topic, so students had the necessary science background. “I definitely think an activity like this would need to be saved for the end of a unit so that students can gather information before they start to apply it to real life applications” (Iris, Reflection #2).

Four participants (18%) expressed the idea that the level of difficulty of the design activity should be appropriate for the age of the students. If the difficulty went beyond students’ actual abilities, they might get lost or even give up. As Hebe wrote, if “it’s too complex for eighth graders to do and I don’t think they will enjoy it because I envision them giving up half way through” (Hebe, Reflection #2). Moreover, considering that students might have little design experience before and need time to be used to it, participants thought that the difficulty of design activity should be increased gradually. At the beginning, the design activity could be less open-ended and students could have some instructions to follow. Later, teachers could choose some more open-ended activity and withdraw scaffolding. For instance, Ella said,

I think it needs to be like a small step kind of thing so that they [students] get to know what it is. Then, they will be open to do it in the future with more in-depth… It is better to have rules or steps to follow. Especially at the beginning if they haven’t been introduced something like that, they might be lost. I think we should teach engineering
design step by step at the beginning. Then, towards the end, they will get a better grasp of it. (Ella, Interview, April 8, 2014)

Knowledge about Assessment

Students could learn a lot from the iterative design process. Therefore, fourteen participants (64%) thought teachers should evaluate not only students’ final products, but also the learning process that they experienced. Teachers could evaluate learning process via formative assessments, such as observation of students’ behaviors, talk with students, and reflection. For instance, in her lesson plan, Demi wrote, “I would walk around the classroom observing how students are interacting with one another… I would ask the student questions to see if they can answer their own questions”. Olga also mentioned “I would not evaluate them solely on their design products. I think I would have a talk evaluation about their science knowledge, design processes, and design experiences” (Olga, Interview, April 17, 2014).

About a third (8) participants (36%) thought teachers should weigh the design process more than the final product, because the aims of teaching are to help students learn science and engineering ideas rather than getting a product. Even if students failed to come up with a product, they may still think and learn a lot from their mistakes. As Paul stated,

Evaluation should focus more on how students solve the problems occurred in design. If they can’t complete design, I will give them grade based on their reflection. I want to see whether they solve the problem by applying science knowledge instead of intuition. I will give them great grades if they have many good thoughts even if they fail to come up with the final products (Paul, Interview, March 23, 2014).
Engineering design is team work. A good final product of a team did not necessarily mean each member did their best and developed their problem-solving ability successfully. Therefore, seven participants thought, besides teamwork, teachers should also assess individuals. The individual assessment could be based on teachers’ observation, individual worksheet, students’ reflection, peer evaluation, etc. For instance, in their lesson plans, Kate stated, “I plan on giving each child an individual participation type grade too. I want to walk around and take notes on how each student uses their time and how they work with the group.” Bess wrote that, she would use “peer evaluation from their group mates” to assess the efforts that individual student put.

The goal of the design activity is to find a solution that meets all criteria. Six participants (27%) thought teachers could design a quantitative rubric by quantifying each criterion whenever it is possible so that students’ final products could be evaluated accurately. For instance, Tess designed a rubric for her boat building activity in her lesson plan. She assigned scores for each criterion, such as time that boat can float, cost of boat, weight that boat can hold, and time spent on building. She also divided the completion of each criterion into several levels according to the degree of fulfillment. In addition, in order to lessen students’ pressure and build a collaborative environment for design activity, four participants (18%) suggested that teachers could use bonus instead of deductive points for some criteria when making rubrics. Just like Yetta mentioned, “I won’t have the students who finish last lose points. I will have the students who finish first get extra bonus points” (Yetta, Reflection #2).

To achieve the goal of engineering design, students need to apply their science knowledge to solve many practical problems. Therefore, three participants (14%) thought engineering design could be a good way to evaluate students’ science learning and provide useful
feedback to teachers’ science teaching. Just as Jane wrote, “Incorporating activities like the hospital circuit system allows students the opportunity to demonstrate their knowledge outside of a typical test format. This also gives teacher the chance to see what concepts may still be confusing to students and needs more elaboration before a formal assessment” (Jane, Reflection #2).

**Conclusions and Implications**

Findings from this case study suggest that a university-based methods course can be an effective setting in which prospective middle-school teachers might develop their knowledge of engineering design, ideas of learning design, and pedagogical insights of teaching design, in order to carry this out in their own classrooms. For instance, all participants developed their understanding of engineering design, including “Defining and delimiting engineering design problems”, “Developing possible solutions”, “Science is the foundation of engineering design”, “The design process is iterative”, “Many workable designs for one task”, and “Each design had its pros and cons”. Participants also acquired knowledge of learning design, such as “Redesigning may be needed”, “Designers may feel frustrated”, “Lots of decision-making involved”, “Teamwork facilitates engineering design”, “Designers need to solve encountered problems”, and “Pinpointing design problems needs science inquiry”. More importantly, participants could transform their knowledge of engineering design and learning design into pedagogical insights of teaching design, including their knowledge of learners, orientation, instructional strategy, curriculum, and evaluation.

Although we only studied twenty-two prospective middle level teachers and their knowledge development process in one learning module, this study does have implications for
the field of science teacher education in terms of helping prospective teachers prepare for teaching engineering design in methods course.

First of all, a methods course should provide prospective teachers with opportunity to experience personal design. This study suggested that a design experience can serve as an important foundation for prospective teachers to develop their knowledge of engineering design and its teaching. Specifically, engaging in design activity could help prospective teachers comprehend the concepts and ideas of engineering design through personal practice instead of rote memorization. For instance, participants developed a deep understanding of model analysis when they tested their circuits and analyzed the pros and cons of their trials. Participants perceived how to optimize their designs when they had to strike a balance among time, cost, and other criteria. In addition, personal design experience also gave prospective teachers the opportunity to go through a similar learning and emotional process that their students might experience. It is important for prospective teachers to develop their ideas of learning design and pedagogical insights of teaching design. For instance, participants emphasized teamwork and encouragement in their lesson plans because, based on their circuits design experience, they experienced engineering design as not an easy task, since it requires creativity and involves higher level thinking. Some participants also experienced negative feelings associated with the design process and started to think about strategies to lessen these when they themselves experienced frustration in circuit design activity. Therefore, we suggest science teacher educators give prospective teachers personal design experience first, so they may have the necessary base upon which their knowledge development could build. This is especially important, given that prospective teachers may have limited or even no previous engineering design experiences prior to taking a science methods class.
Second, the design activity used in methods course should be carefully designed. Engineering design is an area requiring lots of content knowledge. The new science education reform only identified key and basic concepts and ideas for science class. The instructional goals of the design activity should focus on the knowledge required by NGSS. This will help prospective science teachers improve their content knowledge of engineering design, purposefully. For instance, the circuits design activity used in this study centered on the three core ideas and related concepts required by NGSS. In addition, the implementation of a design activity should align with how it could be used in middle school classrooms. By doing this, the design activity could serve as a teaching example to which prospective teachers could refer in their future teaching practice. This will contribute to prospective teachers’ knowledge of teaching engineering design directly and may also inspire their own pedagogical insights. For instance, in this study, participants took some teaching strategies used in circuit design activity in their lesson planning, such as using worksheet to record trials, designing a quantitative rubric to evaluate final products, as well as asking students to make presentations and write reflections after design. Moreover, prospective teachers not only learned the methods used in circuits design activity, but also expanded them, or even proposed many new strategies. For instance, participants suggested that, besides using a quantitative rubric to assess final products, teachers should also use formative assessments to evaluate students’ design process. Moreover, teachers should weigh the design process more than the final products, since the goal of teaching is to promote learning. In addition to evaluating teamwork, individuals should also be assessed to make sure each student learns something from the design activity. Teachers could reduce students’ frustration by reminding them of the iterative features of design process explicitly and keeping on encouraging them.
Third, methods courses should provide prospective teachers with the opportunity to share their design experience and thoughts after design. Prospective teachers may have different experience and generate various ideas even from doing the same design activity. Knowing about others’ design experience and feelings can help prospective teachers develop comprehensive knowledge by deepening their understanding, expanding their thoughts, and avoiding biased ideas. For instance, by designing circuits, prospective teachers realized that they had to modify their designs several times before they got final solutions. Their understanding about the iterative features of design process was further deepened when they saw that no team could achieve the goal only by one trial during presentations. By watching the different designs of other teams, participants realized that, unlike scientific problems, there are many possible solutions for one design task. When sharing their feelings, some participants thought that competition aspect was a good motivator for designers while others argued that competition brought them with pressure and distraction. Participants’ pedagogical insights were developed by discussing how they could take advantage of the competition format and avoid its disadvantages in their future classroom teaching. Therefore, the presentation and class discussions after the design activity were important steps for prospective teachers to share, summarize, and refine their knowledge of engineering design and its teaching with peers.

Finally, a methods course should provide prospective teachers with multiple and diverse design experiences. Although the learning module in this study could help participants gain some understanding about engineering design and its teaching, the knowledge involved in one design activity was limited. In addition, not all participants were able to develop a good understanding of all content ideas and instructional strategies. For instance, only four participants (18%) acquired design strategies, only three participants (14%) emphasized “Encourage students
through design process”, and only two participants (9%) realized “Students have a hard time weighing tradeoffs”. Therefore, prospective teachers need multiple design opportunities to help them widen and deepen their knowledge over time. Besides, the circuits design activity was associated with physics. Employing design activities related to other science subjects may lay emphasis on different design ideas and the requirement for different teaching strategies. 

Employing design activities in other disciplines would help prospective teachers develop a comprehensive understanding of engineering design and its teaching. Moreover, if prospective teachers experience design only in physics, they may develop the misunderstanding that engineering design can only be used to support the teaching of physics concepts and principles.

**Limitations**

This study only focused on prospective teachers’ knowledge development in the context of a university-based methods course. In order to turn their pedagogical insights of teaching engineering design into pedagogical content knowledge (Shulman, 1986), prospective teachers need to have opportunity to translate their new knowledge into a science classroom, and actually teach their own students, interact with their students, and attempt this kind of teaching in the context of their own instruction.
References


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CHAPTER 3

FOCUSING ON CROSSCUTTING CONCEPTS BY INTEGRATING THE NGSS THREE DIMENSIONS: A TEACHING MODEL

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Abstract

Crosscutting Concepts are one of the three dimensions of the new K-12 Science Education Framework (NRC, 2012) and Next Generation Science Standards (NGSS, 2013). Although the idea of crosscutting concepts has been proposed by previous documents for decades, it has not received enough attention from the field of science education. The research for this topic is still very limited and science educators need examples to show them how to design instructions by integrating crosscutting concepts with the other two dimensions urgently. This theoretical study aimed to contribute to this issue by defining the three levels of understanding crosscutting concepts, reviewing the role of learning crosscutting concepts, discussing the principles of teaching crosscutting concepts, and proposing a model of teaching crosscutting concepts. The significance and implications of this research are also discussed.

Key words: crosscutting concepts, science education, teaching model
Introduction

With the release of new United States K-12 Science Education Framework (NRC, 2012) and the latest standards--Next Generation Science Standards [NGSS] (2013), another round of science education reform declares its coming. The recent U.S. reforms pose many challenges for science education researchers and science educators. One of the challenges is how to incorporate the seven sets of crosscutting concepts (CCC) in science teachers’ daily instruction.

Although the new term, *crosscutting concept*, is introduced in the NRC Framework and NGSS, it is definitely not a new idea for the field of science education. Crosscutting concepts are similar to the “common themes” in *Science for All Americans* (AAAS, 1989), the “unifying concepts and processes” in the *National Science Education Standards* (NRC, 1996), and the “unifying concepts” in *Science: College Board Standards for College Success* (College Board, 2009). In fact, the new Framework admits explicitly that “The set of crosscutting concepts defined here is similar to those that appear in other standards documents, in which they have been called ‘unifying concepts’ or ‘common themes’ (NRC, 2012, p. 85)”.

However, despite the fact that the idea of crosscutting concepts has appeared in previous documents for many years, they have received little attention from both researchers and science educators. For instance, when members of the Project 2016 team conducted a review of middle school science curricula, they decided to omit the evaluation factors of “common themes” because they found that there was scarce information about this research field (Kesidou & Roseman, 2002). The new K-12 Science Education Framework also mentioned that “the research base on learning and teaching the crosscutting concepts is limited (NRC, 2012, p. 84)” and “students have often been expected to build such knowledge without any explicit instructional support (NRC, 2012, p. 83)”.

No research tells us why crosscutting concepts have received so
little attention from science education researchers, although these concepts have been identified and emphasized by previous documents for decades. In order to elevate the role of crosscutting concepts, the NRC decided to set up crosscutting concepts as a separate dimension with the same status as the other two dimensions—Practices and Disciplinary Core Ideas (DCI)—so that crosscutting concepts can draw more attention from the field of science education (NRC, 2012).

In this paper, we will first discuss the role of crosscutting concepts, the cognitive levels of understanding crosscutting concepts, and the principles of designing crosscutting concepts instruction. Then we propose a model of teaching crosscutting concepts. We also present an example to illustrate how the teaching model could be used in K-12 science education. Finally, we discuss the significance and implications of this research.

**The Roles of Crosscutting Concepts**

Crosscutting concepts are important themes that transcend disciplinary boundaries (AAAS, 1989). They “have value because they provide students with connections and intellectual tools that are related across the differing areas of disciplinary content (NRC, 2012, p. 218)”. Specifically, crosscutting concepts are interdisciplinary bridges which can connect various scientific fields, link science with technology, engineering, and mathematics (STEM), and help transfer science knowledge to other non-scientific areas as well as our daily lives.

First of all, crosscutting concepts are important for interdisciplinary science education. Traditional discipline-based science education only focuses on the knowledge and problem-solving skills of particular disciplines. Many researchers raised the criticism that discipline-based science teaching and learning can only provide students with discrete and fragmental knowledge and skills (e.g. diSessa, 2002; Dreyfus et al., 2011; Redish, Saul, & Steinberg, 1998). When
dealing with complex real-world problems that require knowledge from multiple scientific disciplines, students may suffer from their isolated knowledge and discipline-specific skills. Not surprisingly, more and more attention has been drawn to interdisciplinary science education (e.g. AAAS, 2009; AAMC/HHMI. 2009; NRC, 2005). Crosscutting concepts are common ideas used in various scientific fields. Therefore, crosscutting concepts could be robust and powerful cognitive tools that help students think about transcending disciplinary boundaries, facilitate their interdisciplinary scientific reasoning, and improve their ability of solving interdisciplinary scientific problems.

Second, crosscutting concepts can promote STEM (Science, Technology, Engineering, and Mathematics) education. Crosscutting concepts are the important themes pervading science, technology, engineering, and mathematics repeatedly (AAAS, 1989). For instance, we can see pattern in the repeated base pairs of DNA, in an arithmetic or geometric progression, in the field of software design engineering, or in various pattern matching technology. Crosscutting concepts have similar meanings in different areas. Therefore, students’ comprehension of a certain crosscutting concept will pave the way for their future learning of it in other STEM fields. For instance, after students develop a good understanding of scale in their math classes, they can easily comprehend the number of atoms in an object, the size of Nano technology, and the scale in engineering drawing. This will be conducive to the integration of STEM fields.

Third, crosscutting concepts are the interdisciplinary bridges which link science with other non-scientific fields and even our daily lives. Crosscutting concepts are not the unique ideas of science. They are general and universal themes emerging in almost all fields and even in our daily lives (Gross & Fordham, 2011; Jin & Anderson, 2012; NRC, 2012). In fact, that is also one of the powers and beauties of these crosscutting concepts. It means that crosscutting
concepts can act as reasoning blocks or analytical vehicles to facilitate students’ transfer of their scientific knowledge not only to their learning of other non-scientific fields, but also to their everyday lives. The former transfer will help students realize the value and significance of scientific knowledge, thinking, and reasoning. The latter transfer is crucial for developing students’ scientific habits of minds. In fact, the latter transfer is also the ultimate goal of scientific inquiry advocated by Dewey (1938) and is critical for cultivating qualified citizens.

Three Levels of Understanding Crosscutting Concepts

According to the interdisciplinary nature of crosscutting concepts, we propose that students’ understanding of crosscutting concepts in science education can be divided into three levels. From lower to higher these are 1) common sense level; 2) disciplinary level; and, 3) interdisciplinary level.

Common sense level means simply that students’ understanding of the crosscutting concepts are based on the common sense which they developed in their everyday lives. As mentioned above, crosscutting concepts are not the unique ideas of science, they are also the universal themes in our daily lives (Gross & Fordham, 2011; Jin & Anderson, 2012; NRC, 2012). Therefore, students will have their own basic understanding about crosscutting concepts based on their personal life experiences before they come into science classrooms. In fact, many crosscutting concepts have been an integral part of our lives for so long that children may not realize these ideas are also important themes of scientific fields, although they have already developed some preliminary comprehension of these concepts. For instance, when selecting clothes in shop, young people will consider the pattern on the clothes. When feeling tired after a sport competition, young people know they need more energy. When children are curious about
some strange things (*effect*), they usually ask why and want to know about the *cause* of the occurrence of these phenomena. When playing with LEGO, children know the *structure* will influence the *function*. Children will compare the *quantity* of the snacks or the scores are assigned to them, as compared with their peers. When building sand castles, kids know they are just *models* which resemble castles rather than being the real castles.

The second level of understanding crosscutting concepts is disciplinary level. It refers to the fact that students develop progressive understanding about these crosscutting concepts, by learning them in specific disciplinary contexts. Therefore, students’ understanding of crosscutting concepts at this level has moved beyond their common sense comprehension to a higher level through their learning experiences of disciplinary knowledge. For example, students’ understanding of *energy* may be expanded by learning about kinetic and potential energy in physics, conserved energy in chemical reaction, or energy flow in photosynthesis in plants. Students’ initial impressions of *structure and function* may be deepened by studying the structure and function of atoms in chemistry, structure and function of bridges in physics, or structure and function of human body in biology. Although understanding crosscutting concepts at this disciplinary level is higher than the common sense level, it is still constrained by disciplinary boundaries or perspectives. In other words, students’ comprehension of crosscutting concepts at disciplinary level is still embedded in their understanding of disciplinary ideas and has not developed into an independent knowledge system yet. Therefore, this disciplinary understanding of crosscutting concepts that needs to be supported by disciplinary context is not ready to be transferred across disciplinary boundaries. In order to achieve the “interdisciplinary bridge” function of crosscutting concepts, students need to continue to improve their comprehension of crosscutting concepts to the highest level—interdisciplinary level.
Interdisciplinary level understanding of crosscutting concepts means that students’ comprehension of crosscutting concepts will not suffer from the restriction of disciplinary boundaries anymore. Saying this in another way, students’ understanding has moved beyond the contexts of specific disciplines and starts to develop into an independent knowledge system of crosscutting concepts. Therefore, students can understand crosscutting concepts in a general manner without the support of concrete disciplinary scenarios. Understanding crosscutting concepts at this interdisciplinary level will help students transfer their scientific reasoning across different disciplines more freely, learn knowledge from other disciplines more easily, and solve interdisciplinary problems more comfortably. For instance, after students know that *system* consists of boundaries, components, resources, flow, and feedback (NRC, 2012), they can use this knowledge of system to analyze problems about interdisciplinary systems, like a climate change system. Understanding crosscutting concepts at the interdisciplinary level can serve as an analytical tool providing students with the integral perspectives or lens to conduct interdisciplinary inquiry in broad scientific areas, STEM fields, non-scientific areas, or even in their everyday lives.

The relationship between the three-level understandings of crosscutting concepts is that lower level comprehension is the foundation for the higher level understanding. First of all, students’ disciplinary comprehension of crosscutting concepts should be built on their common sense understanding. Many learning theories emphasize that teachers should consider students’ prior knowledge when they design their instructions. For instance, the learning perspective of constructivism provides the foundation for teachers to help students construct their own knowledge structures by building on their existing knowledge (Matthews, 1998); The learning perspective of knowledge integration suggests that students’ learning should be developed by
integrating students’ prior and to-be-learned knowledge (Linn, 2006); The theory of conceptual change highlights that students are not "empty vessels" and they may hold alternative conceptions before they receive formal education. Teachers should elicit and clarify students’ alternative conceptions before interventions can begin (Posner et al., 1982). The teaching of crosscutting concepts should follow these learning principles by considering students’ previous comprehension of crosscutting concepts which are generated from personal life experiences (NRC, 2012).

Similarly, the interdisciplinary understanding of crosscutting concepts should be based on students’ disciplinary understanding of these concepts. According to the new K-12 Science Education Framework, the seven sets of crosscutting concepts are expected to be the interdisciplinary bridges which connect different scientific disciplines (NRC, 2012). Therefore, the ultimate goal of teaching crosscutting concepts is to help students achieve the interdisciplinary level rather than the disciplinary level understanding. However, Just as Gross and Fordham (2011) wrote, “they [crosscutting concepts] are very high-level constructs, whose real significance may be grasped by able and relatively mature pre-collegiate students but not by many others, even in the final years of high school (p. 19).” Therefore, in order to make crosscutting concepts less abstract and more accessible to K-12 students, the interdisciplinary understanding of crosscutting concepts should not be achieved by teaching students the abstract meaning of these concepts via boring explanation. Rather, the interdisciplinary understanding of crosscutting concepts should be developed in the specific disciplinary learning experiences incrementally (NRC, 2012), such as learning disciplinary core ideas, as well as doing disciplinary inquiry and engineering design projects.
Principles of Teaching Crosscutting Concepts

According to our discussion above, we argue science teachers should consider the three levels of understanding crosscutting concepts when they design their science instruction. In other words, the three levels of understanding crosscutting concepts should be one of the principles of teaching these concepts. Besides the three-level-understanding guideline, other aspects also need to be considered when teachers are designing the instruction of crosscutting concepts. We will discuss each of these aspects in the following section.

As one of the three dimensions of the new K-12 Science Education Framework and NGSS, crosscutting concepts should be taught by integrating with the other two dimensions — Practices and Disciplinary Core Ideas (Achieve, 2013; NRC, 2012). Crosscutting concepts have a close relationship with disciplinary core ideas. As aforementioned, students’ understanding of crosscutting concepts can be divided into common sense level, disciplinary level, and interdisciplinary level. The highest-level — interdisciplinary understanding of crosscutting concepts should be built on students’ disciplinary comprehension of these concepts. And, students’ disciplinary understanding of these concepts needs to be embedded in the learning of disciplinary core ideas. Therefore, learning crosscutting concepts needs the support from disciplinary core ideas. Besides disciplinary core ideas, the teaching of crosscutting concepts also requires use of science and engineering practices in instruction. Put it another way, as abstract constructs, crosscutting concepts need to be taught by conducting scientific inquiry and doing engineering design activity. Without engaging students in the practices, teachers have to rely on didactic lecture to teach the abstract meaning of crosscutting concepts. By engaging students in doing practices, students will experience a more concrete and effective learning environment to comprehend crosscutting concepts. Therefore, crosscutting concepts should be taught by
integrating with practices and disciplinary core ideas. This is not only the requirement of new science education reform, but also the inner demand of learning crosscutting concepts.

Third, the learning objectives for crosscutting concepts should be appropriate for students’ grade level (NRC, 2012). Teachers need to consider students’ mental maturity and cognitive abilities when designing their instruction. This is especially important for teaching crosscutting concepts because of their inherent abstractness. Both using lower and higher learning objectives other than those related to students’ actual capability will adversely affect students’ interests in learning crosscutting concepts. Specifically, focusing on lower learning objectives of crosscutting concepts will make students perceive these ideas as self-evident and they may be unable to realize the significance of these concepts. On the contrary, if the learning objectives of crosscutting concepts are too much for students, they may not be able to comprehend the profound meanings involved in them. Therefore, science educators should refer to the NGSS to determine the appropriate difficulty for the instruction of crosscutting concepts.

Fourth, crosscutting concepts should be taught explicitly (NRC, 2012). First of all, the terms of the crosscutting concepts should be taught explicitly. Crosscutting concepts are interdisciplinary bridges that connect different disciplines. Therefore, the terms are important vocabulary for students to communicate their ideas or reasoning process across disciplines (NGSS, 2013). Teachers have responsibility to help students build their interdisciplinary vocabulary by talking about these terms explicitly and frequently in science classes. Second, the ideas included in the crosscutting concepts should also be taught explicitly. Teachers should not anticipate that K-12 students are sensitive to crosscutting concepts and able to comprehend these abstract constructs interweaved with disciplinary core ideas without any necessary scaffolding.
Therefore, science teachers should help students reflect on the crosscutting ideas embedded in the learning process of disciplinary knowledge and practices deliberately.

Fifth, according to Bloom’s taxonomy (Anderson & Krathwohl, 2001), the learning objectives in the cognitive domain can be divided into six levels. From lower to higher level, they are Knowledge, Comprehension, Application, Analysis, Synthesis, and Evaluation. Similar to learning science concepts and principles, learning crosscutting concepts should not stop at the interdisciplinary understanding level. Students should be given opportunities to achieve learning crosscutting concepts at a higher level, such as that of application, analysis, synthesis, and evaluation. Moreover, considering the interdisciplinary essence of crosscutting concepts, students should have the chance to apply “their understanding of the crosscutting concepts in the contexts of specific applications in multiple disciplinary areas (NRC, 2012, p. 218)”. For instance, students’ interdisciplinary comprehension of crosscutting concepts can be applied as analytical tool to help them learn new ideas from various disciplines, analyze new problems in different disciplinary contexts, or evaluate opinions from different disciplinary issues. This high level learning process will not only benefit students’ learning of crosscutting concepts by helping them deepen their understanding of these concepts in the new contexts or problem scenarios, but also facilitate their learning of new disciplinary core ideas and practices. Moreover, besides various disciplinary contexts, students’ interdisciplinary understanding of crosscutting concepts can also be applied to their daily lives. This will be very helpful for cultivating students’ scientific habits of minds. For instance, students may evaluate the reliability of the news about science or make their judgments about their everyday lives by synthesizing their comprehension of crosscutting concepts. This application of crosscutting concepts in everyday lives will inevitably influence students’ understanding of crosscutting concepts at the common sense level.
Finally, the teaching of crosscutting concepts should be incremental, through multiple learning cycles in various disciplinary contexts. “Crosscutting concepts should grow in complexity and sophistication across the grades (NGSS, 2013, appendix G)”. When planning science teaching, teachers should consider students’ previous informal and formal learning experiences of crosscutting concepts and try to build the new learning on the students’ prior knowledge to facilitate their learning progression of these concepts. Moreover, this learning progression should be achieved through long-term iterative teaching using multiple disciplinary contexts, across grade level, because of the abstract and interdisciplinary features. Along with this spiral learning progress of students’ understanding of crosscutting concepts, their learning of crosscutting concepts in the context of everyday lives should also be cultivated gradually through multiple cycles of learning practice. In one word, the learning process of crosscutting concepts should be achieved through an interdisciplinary cumulative progress, as opposed to a one time or even, simply a repetitive teaching approach in one specific discipline.

A Model of Teaching Crosscutting Concepts

Based on the discussion above, we propose a model of teaching crosscutting concepts that could be used in K-12 science education (Figure 3.1). In this model, students' understanding of crosscutting concepts consists of three levels as we defined. After students achieve the highest level understanding (interdisciplinary level), their knowledge of crosscutting concepts could be used as an analytical tool to help them learn more disciplinary core ideas and influence their daily lives by promoting their scientific habits of minds. This will be achieved by applying their knowledge of crosscutting concepts in the context of scientific inquiry and engineering design activities in science classes. One point that needs to be stressed is that students’ understanding
of a specific crosscutting concept needs to be reinforced and deepened through latter learning cycles. In other words, this teaching model is not only a single cycle. Rather, it emphasizes the spiral process of learning crosscutting concepts. Next, we describe teaching about Magnetic Field, as an example of how to design effective instruction of crosscutting concepts by applying our proposed teaching model.

Magnetic field is not only an important disciplinary core idea of 8th grade physical science, but also a difficult topic to teach due to its invisibility. Magnetic field is very abstract for middle school students because, although students know magnet can attract metals, they cannot actually see magnetic field with their naked eyes. The important analytical tools involved in the teaching of magnetic field are the crosscutting concepts---- System and System Model. By developing the system model (Practices dimension) of Magnetic field----Magnetic Field Lines,
students can not only acquire the knowledge of magnetic field and magnetic force (DCI dimension), but also develop their understanding of system and system model themselves (CCC dimension).

**Three Levels of Understanding System and System Model**

First, teachers need to identify the starting point of instruction by considering both middle school students’ prior knowledge of system and system model, and their common sense understanding of them. The former can be figured out by consulting relevant learning objectives for elementary science and the latter can be identified by considering their students’ possible life experiences. For instance, students in elementary school have learned that a system consists of related parts; system has the function its parts cannot perform individually (NGSS, 2013); physical models can be used to represent real objects; there are some similarities between the real objects and their physical models (AAAS, 1989). All the ideas students have obtained in their elementary schools become middle school students’ prior knowledge of system and system model. According to these learning objectives of system and system model for elementary science education, we can infer that middle school students’ prior knowledge of system and system model is very limited. In addition, students may have some ideas about a conceptual model, although it is not listed in the learning objectives for elementary science. Specifically, students’ life experiences may provide them with preliminary comprehension of conceptual model which consists of students’ common sense understanding of system model. For instance, kids may draw some spots to represent air, use some straight lines or curves to stand for light from the Sun or the water in rivers. Because all of these preliminary impressions of conceptual
model come from children’s drawing experiences instead of their formal science learning experiences, they belong to students’ common sense understanding of system model.

Second, science teachers need to consider the specific learning objectives for the interdisciplinary understanding of system and system model. These interdisciplinary learning objectives can be identified by consulting the requirement of system and system model from the new K-12 Science Education Framework, NGSS, and relevant literatures. For instance, according to the NGSS, knowledge of system and system model for grade 6-8 includes: a system may interact with other systems; complex systems consist of sub-systems; system models can be used to represent interactions within systems; system models have their limitations. Besides physical models, middle school students should know that conceptual representations are also helpful for studying system (Schwarz & White, 2005). All of these ideas of system and system model which are relevant to the topic “magnetic field” are suitable for teaching 8th grade students. Moreover, all of these ideas are the interdisciplinary understanding of system and system model because these ideas are abstract knowledge about crosscutting concepts themselves without the contexts of disciplinary core ideas or practice, and therefore, can be generalized to any scientific disciplines.

Next, teachers need to consider how to facilitate students in gaining a disciplinary-level understanding of system and system model based on students’ prior knowledge, common sense understanding of these concepts, and the requirement of interdisciplinary understanding discussed above through teaching core ideas and engaging in activities of magnetic field. For instance, after observing that a magnet can attract steel paper clips and two magnets may attract or repel each other, students know there is something special around magnets. Then, in order to study the magnetic field, teachers can guide students to first choose their system (i.e. one magnet
as a system or two magnets as a system). Teachers can also help students actually see a magnetic field by using filings to create a physical model of it. Specifically, if students put magnets at the center of a plastic sheet, sprinkle iron filings onto the sheet, and, then, knock the sheet gently, the pattern of the iron filings will be the shape of the magnetic field of the magnets. This physical model will make an invisible magnetic field materialize. Based on what children observe, teachers can then ask them to think about how to draw the conceptual model for magnetic fields, just like they used spots, curves, and lines to represent air, water, and light. All these teaching activities are built on students’ prior knowledge of system and physical model that they have learned in elementary schools, and their common sense understanding of conceptual model.

Students’ learning of system and system model can also be expanded during the learning process of magnetic field. For instance, besides physical model, teachers can also use inquiry activities to help students construct the conceptual model of magnetic field—magnetic field lines. One inquiry activity could be using a small compass to make a map of a magnetic field of a bar magnet by drawing the locations of the compass and the directions of the compass needle. In doing this inquiry activity, students can develop their conceptual model for one bar magnetic field by mapping out the magnetic field lines. Another inquiry activity may be mapping out the magnetic field of two bar magnets with their poles facing each other. During this activity, teachers can teach students additional knowledge of system by building on their prior knowledge about this concept. For instance, teachers can mention that when studying simple problems, like the magnetic field of one bar magnet, we do not need to clarify the system that we have chosen because there is only one object. The only object will be regarded as the defaulted system tacitly. When studying the magnetic field caused by two bar magnets, there will be interaction between these two systems. At this time, magnetic field line is a good conceptual model to study this
interaction between the two magnets. In addition, teachers can also tell students that another way to analyze this problem is that we regard the two bar magnets as one system and the two bar magnets as its sub-systems. Sometimes, this whole system perspective may simplify complex problems by overlooking the interactions between sub-systems.

When regarding each bar magnet as a system, the two bar magnet systems will interact with each other; we can use magnetic field lines, this conceptual model, to represent the interaction between the two bar magnet systems; when the two bar magnets are considered as a whole system, this system consists of two sub-systems; we may overlook the interactions among the two bar magnets since we regard them as a whole system. All of this knowledge about magnetic field contains new knowledge of system and system models required by NGSS and literatures for middle school students. Moreover, when doing the inquiry activities (i.e. materializing the invisible magnetic field with iron filings; mapping out the magnetic fields of one bar and two bar magnets), students will not only learn physics core ideas (e.g. the magnetic field is strongest at the poles; the direction of magnetic field; using magnetic field lines describe magnetic field), but also experience every aspect of scientific practice, like asking questions about magnetic fields, collecting data and analyzing data (e.g. record location of compass, draw the direction of magnetic field in specific locations; figure out the patterns indicated by their data; interpret the patterns showed by iron filings or compass), communicating or even arguing for their different ideas about what magnetic fields may look like with their peers, and so forth.

Besides doing activities, science teachers can also help students develop their disciplinary understanding of system and system model by asking them to think about some inspiring questions or solve some interesting problems. For instance, how to use magnetic field lines to figure out the direction of the magnetic field in a location between two adjacent lines? How to
compare the magnitudes of the magnetic field of two points which are out of the plane of the magnetic field lines? When thinking about these questions, students will find that although there is “empty” between two adjacent magnetic field lines, there is still magnetic field there. Although the map of magnetic field is two dimensional, the real magnetic field is three dimensional. These questions will help students realize the limitations of using magnetic field lines—this conceptual model to describe magnetic field.

One point that needs to be emphasized is that teachers should not anticipate that middle school students can achieve interdisciplinary understanding of system and system model naturally by realizing the abstract meaning of these concepts that is encapsulated in the knowledge and practices about magnetic field. In other words, the terms and ideas of crosscutting concepts should be taught explicitly and deliberately as we have stressed. Therefore, after students gain a disciplinary understanding of system and system model, teachers should help students distill the interdisciplinary comprehension of system and system model (e.g. complex systems consist of sub-systems; system models can be used to represent interactions within systems; system models have their limitations) by scaffolding, like asking students to reflect on their knowledge about magnetic field and inquiry process about magnetic field lines. In addition, the terms of system and system model should also be used explicitly during the whole teaching process.

Further Learning of System and System Model

As preceding discussion suggested, students’ learning of crosscutting concepts should not stop at the level of knowledge and comprehension. Science teachers have the responsibility to provide students with multiple opportunities to apply their interdisciplinary understanding of
system and system model as analytical tool to learn other new scientific knowledge or solve complicated scientific problems. These further learning experiences will contribute to not only the reinforcement and increment of students’ knowledge of system and system model, but also the deepening and expansion of their disciplinary core ideas and the implementation of practices (NRC, 2012). Moreover, this further learning process will involve not only physics, but also every other scientific disciplines (e.g. astronomy, biology, and chemistry) due to the interdisciplinary essence of system and system model. In the following we provide two examples.

The first example is that of high school physics, when studying disciplinary core ideas, like forces and energy in a complicated problem that involves many objects. In this case students may need to change their studying of systems several times during their problem solving process. Specifically, when studying interactions among components, students may need to choose each component as their studying system. When studying the total force or energy of the problem, students may need to regard all components as a whole system. Moreover, students will not only use their prior knowledge of system (e.g. complex systems consist of sub-systems; system components have interactions) to reason complicated problems, but also expand their knowledge of system in the new physics contexts. For instance, students may need to define the boundaries and initial force or energy states of a system; study the input and output energy of the system; use system model to predict the force or energy change of system.

The second example is that of studying Coulomb’s Law in high school physics. Students’ prior knowledge of system model can help them understand that system model (i.e. point charges) can be used to study interactions (i.e. electrostatic forces) within systems. Students can also use their prior knowledge of system model (i.e. system models have their limitations) to infer that
there may be some limitations about point charge model. Besides applying prior knowledge, students’ comprehension of system model can also be expanded in the context of learning Coulomb’s Law. For instance, students may feel puzzled about the “point charge” model because this conceptual model may seem totally different from the real objects. Specifically, students may feel comfortable about using a little point to stand for a small object. But, it may be difficult for them to understand that we can use a point without any volume to represent a very big charged body. By studying that point charge is only the approximation of charged objects by ignoring the minor aspects (i.e. the volumes) and highlighting the major factor (i.e. electrostatic forces) of problems in order to simplify our reasoning, students will deepen their understanding about the limitation of system model. For instance, when using the “point charge” model to predict the magnitude of the electrostatic force between two charged balls that possess the same kind of charges, students will find that the actual magnitude of the electrostatic force between the two objects is smaller than the calculated value. This is because same kind of charges repels each other and the actual distance between charges on the two balls is longer than the distance between the centers of two balls. This practical problem will help students realize that “predictions have limited precision and reliability due to the assumptions and approximations inherent in the models” (NGSS, 2013, appendix G).

Besides physics, students’ understanding of system and system model will also have the opportunities to grow in other disciplinary contexts and benefit their future learning of other scientific disciplines, like the photosynthesis model of a leaf, an ecosystem model, and the cellular respiration model in life science; the solar system model and the greenhouse effect model in earth sciences; the atom structure model, chemical bonding model, and electric cloud model in chemistry.
In addition, students’ comprehension of systems and system models can also be applied to and improved in STEM fields and their daily lives. For instance, modeling design is the core of engineering design. While students’ knowledge of a system model facilitates their design process, their understanding of system model will also get reinforced and developed in the design context. Furthermore, students’ understanding of system and system model can also benefit their daily lives. For instance, when students try to convey their ideas with others, they can use physical or conceptual models to describe them; when studying complex issues, students can divide the problem system to several sub-systems; students will consider the limitation of their own system models when constructing them; when evaluating the system models proposed by others, students may be sensitive to the limitations of the models. All of these personal life practices will deepen students’ knowledge of system and system models, facilitate the development of their scientific habits of minds, and stimulate their interests of learning science.

**Significance and Implications**

This theoretical paper may contribute to science education by shedding light on the research of crosscutting concepts—the second dimension proposed by the new K-12 Science Education Framework and NGSS—from both theoretical and practical perspectives. First of all, crosscutting concepts are important themes pervading science, STEM, and even in our daily lives (Gross & Fordham, 2011; Jin & Anderson, 2012; NRC, 2012). However, as mentioned above, crosscutting concepts have not received sufficient attention, although it has been emphasized for a long time. “The research base on learning and teaching the crosscutting concepts is limited” (NRC, 2012, p. 84). This paper contributes to this issue theoretically by defining the three levels of understanding crosscutting concepts, reviewing the roles of crosscutting concepts, and
discussing the principles of teaching crosscutting concepts. Second, the new K-12 Science Education Framework and NGSS require science educators to teach science by integrating the three dimensions—Practices, Crosscutting concepts, and Disciplinary Core ideas. This goal is very clear. However, how to achieve this goal is a challenging task. “Examples of how it can be achieved are needed” and “there is no single approach that defines how to integrate the three dimensions” (NRC, 2012, p. 217). The teaching model proposed in this theoretical paper provides one practical way to achieve this integration goal from crosscutting concepts’ perspective.

Implications for science educators’ teaching practice of crosscutting concepts include the following. First, there are similarities and differences between teaching crosscutting concepts and other scientific concepts. For instance, like other scientific concepts, the learning of crosscutting concepts should be built on students’ prior knowledge, including both their previous school learning experiences and their common sense understanding generated from everyday lives. Moreover, as revealed by Bloom’s taxonomy, students’ learning objective should include not only Knowledge and Comprehension level, but also other higher level, like Application, Analysis, Synthesis, and Evaluation. All of these are the similarities between teaching crosscutting concepts and other disciplinary ideas. However, unlike learning other scientific concepts, students’ comprehension of crosscutting concepts includes not only disciplinary understanding, but also interdisciplinary understanding due to the interdisciplinary essence of crosscutting concepts. Therefore, students’ learning of crosscutting concepts should not terminate at the disciplinary level. Science teachers need to help students distinguish their interdisciplinary understanding of crosscutting concepts from their disciplinary comprehension by reflecting on the essence of disciplinary core ideas and practices.
Second, the teaching of crosscutting concepts needs to break disciplinary boundaries. Crosscutting concepts are expected to be the interdisciplinary bridges that link different scientific areas and STEM fields. Therefore, students should be given opportunities to apply “their understanding of the crosscutting concepts in the contexts of specific applications in multiple disciplinary areas (NRC, 2012, p. 218)”. Accordingly, science teachers need to know what knowledge of crosscutting concepts that their students have acquired not only from their own disciplines, but also from other scientific disciplines and engineering practices so that teachers can make clear students’ actual starting point of learning. In other words, besides his or her own subject, science teachers should also have curriculum knowledge of other disciplines (Shumlan, 1986).

Third, the teaching of crosscutting concepts should be extended to students’ daily lives. The ultimate goal of science education is to help students transfer their scientific knowledge and practices to their lives (Dewey, 1938). Crosscutting concepts are not only the themes in science and STEM fields, but also the important ideas involved in daily lives that can facilitate the development of students’ scientific habit of minds and influence students’ common sense understanding of these important themes. Therefore, science teachers may need to inspire students how to use the ideas of crosscutting concepts to explain the phenomena, analyze the problems, evaluate the opinions, or make decisions in their life experiences by giving students specific application examples and providing them with the opportunity to practice.
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CHAPTER 4

LEARNING TO TEACH SCIENCE BY INTEGRATING THE THREE DIMENSIONS IN NGSS

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3 Zhang, D. and B. A. Crawford. To be submitted to the *Journal of Science Teacher Education*. 
Abstract

The new K-12 Science Education Framework (NRC, 2012) and Next Generation Science Standards [NGSS] (2013) advocate teachers teach science by integrating three dimensions – Practices, Crosscutting concepts, and Disciplinary Core Ideas. Therefore, helping prospective teachers prepare for the new three-dimension teaching approach is an imperative task for the field of science teacher education. In this multiple-case study (Yin, 2014), we investigated the beliefs of four prospective middle-school teachers’ about the three-dimension approach, as well as their intentions and practices related to the approach in their practicums. Data included pre-questionnaire, three reflections, post-questionnaire, semi-structured interviews, and researchers’ journals. The inductive method (Erickson, 1986) and cross-case analysis technique (Yin, 2014) were used to analyze the data. This study had several conclusions. First, participants’ belief development about the three-dimension approach is a complex process involving many factors. Second, although prospective teachers recognized the benefits of the three-dimension approach, they also had concerns about it. Third, prospective teachers’ beliefs about the new three-dimension approach were emerging and needed to be further cultivated. Finally, prospective teachers’ belief enactment was influenced not only by their beliefs about the three-dimension approach, but also by other beliefs in their belief systems and contextual factors.

Key words: prospective teacher, teacher beliefs, three dimensions, NGSS
Introduction

The new K-12 Science Education Framework (NRC, 2012) and Next Generation Science Standards [NGSS] (2013) indicate the arrival of another round of science education reform in the United States. The ideas of the new reform stem from prior documents, but extend them in substantial ways (Reiser, 2013). For instance, previously, inquiry (NRC, 1996) was the major approach for teaching science. In the new reform, scientific inquiry is expanded to the Practices (Ps) dimension which contains not only scientific inquiry, but also engineering design. In order to help students develop a coherent understanding of science, the ten “common themes” (AAAS, 1989), five “unifying concepts and processes” (NRC, 1996), and seven “unifying concepts” (College Board, 2009) are developed into seven sets of Crosscutting Concepts (CCC). In addition, the new reform shifts attention away from the breadth of the content knowledge and chooses to focus on students’ deep understanding of a certain amount of Disciplinary Core Ideas (DCI). Engineering and Science Practices (ESPs), CCC, and DCI consist of the three dimensions of the new Framework and NGSS. The new reform emphasizes the significance of the three dimensions for students’ learning. Moreover, in order to reflect the interconnected nature of science, the reform suggests teachers to teach science by integrating the three dimensions rather than introducing them in separate ways.

Although the implementation of education reform is a systematic work affected by various factors, the quality of the teacher is often regarded as the most critical element (Bybee, 1993; Calderhead, 1996; Crawford, 2007; Cuban, 1990; Levitt, 2002). After all, we cannot expect education reform to be carried out successfully without qualified practitioners. However, integrating three dimensions in instruction is challenging for science teachers considering that this is a new teaching approach and teachers themselves may have few, or even none related
learning experience. To make matters worse, there are no adequate examples to show teachers how to do it (NRC, 2012). Therefore, helping prospective teachers prepare for the new three-dimension teaching approach is an imperative task for the field of science teacher education.

In this study, we investigated prospective middle-school teachers’ beliefs about the three-dimension approach, as well as their intentions and practices related to the approach in their practicums.

Overview of the Study

The study was partially embedded in a methods course in the Fall 2013 semester at a southern university in USA. The researchers were the instructors of the course. Twenty-four prospective middle-school teachers, including 20 undergraduates and 4 graduates, enrolled in the class. One of the goals of the course was to help prospective teachers learn the three-dimension approach in the context of middle-school science. Although the Practice dimension contains both scientific inquiry and engineering design, the course only touched upon the former considering that it was an exploratory efforts about three-dimension approach. Moreover, not all performance expectations in NGSS require both scientific and engineering practices. Therefore, the practices dimension in this study focused primarily on the science aspect, and not the engineering one. Before starting the course, prospective teachers responded to a pre-questionnaire about their initial knowledge and beliefs about the three-dimension approach.

The methods course consisted of three learning stages (Figure 4.1). The first stage focused on prospective teachers’ learning of the dimensions since “the integration of the dimensions will be most effective if educators have a thorough and clear understanding of each dimension” (Harold Pratt, 2012, p 26). Specifically, the first stage helped prospective teachers learn the eight aspects of scientific practices and seven sets of crosscutting concepts. Although
disciplinary core ideas are also one of the three dimensions, we did not assign special time to them. First of all, it was a methods course rather than a science content course. Second, although disciplinary core ideas are not generally the focus of a methods course, they are the necessary background knowledge for learning about scientific practices and crosscutting concepts. Therefore, prospective teachers would have opportunities to deepen their understanding of disciplinary core ideas when they engaged in teaching about scientific practices and they worked towards comprehending crosscutting concepts. During this stage, prospective teachers learned every aspect of scientific practices by engaging in three inquiry activities, including Mystery Tube, Seed Germination, and Leaf Classification. They learned crosscutting concepts by reading articles, attending lectures, and discussing in groups. In the second stage, prospective teachers experienced the integration of the three dimensions by doing four classroom investigations, including Bottle Biology, Moon Phases, The Pond Project, and Fossil Finders. Specifically, in the Bottle Biology project, prospective teachers studied plant growth (DCI) by analyzing its cause (CCC) and carrying out an investigation (Ps). Prospective teachers learned about the phases of the moon (DCI) and about patterns (CCC) by building models and constructing explanations (Ps) in the Moon Phase project. They drew a food web (DCI) of a pond by studying the pond system (CCC) and developing models (Ps) in the Pond Project. They studied about geological time (DCI) and time scales (CCC) by interpreting and analyzing data (Ps) in the Fossil Finder project. In the last stage, prospective teachers practiced how to integrate the three dimensions by translating their learning experiences and thoughts developed from the first two stages into practical knowledge and skills. Specifically, they critiqued two chapters of a middle-school science textbook from the three-dimension’s perspective. They also designed their own unit plans according to NGSS. During the entire semester, prospective teachers reflected on their
experiences and insights by writing a reflection for each learning stage. The researchers kept journals to record classroom observations, class discussions, and informal conversations with prospective teachers. At the end of the methods course, prospective teachers completed a post-questionnaire about their belief development process and ending beliefs about the three-dimension approach.

During this same semester, the prospective teachers in the methods course also went to local schools and started their practicum experience. Although the state was one of the states that led the development of NGSS, it had not adopted it at the time of this study. Therefore, these practicum schools were still using the old state standards. Considering that NGSS had not been used by teachers in these schools, the instructors of the methods course encouraged the prospective teachers to use the three-dimension approach to teach science in their practicums. But, whether or not these prospective teachers used the approach depended on the prospective teachers themselves. After the practicum ended, the researchers interviewed the prospective teachers about their learning experiences in the methods course, as well as their experiences, thoughts, and practices related to the three-dimension approach.
The following research questions are included in this study:

(1) How do prospective middle-school teachers’ beliefs about the three-dimension approach develop during the semester?

(2) What beliefs about the three-dimension approach did prospective middle-school teachers acquire by the end of the semester?

(3) In what ways, if any, did prospective middle-school teachers endeavor to teach science via the three-dimension approach in their practicums?

(4) What factors influenced prospective middle-school teachers’ beliefs enactment related to the three-dimension approach in their practicums?

**Conceptual Framework**

Teacher beliefs have been regarded as “the most valuable psychological construct” (Pintrich, 1990) that could be used to explain and predict the differences in teacher’s behaviors (Fives & Buehl, 2012). Researchers also found that teacher beliefs play an important role in teachers’ decision-making process, such as what should be taught to students, what teaching approach would be appropriate, and how much time should be assigned to the topic (Cronin, 1991). However, although teacher beliefs have been studied for several decades, there is no consensus on its definition. Defining teacher beliefs has become “a game of player's choice” (Pajares, 1992, p. 309). Teacher beliefs have been assigned diverse meanings by scholars from various perspectives. For instance, teacher beliefs have been used in different contexts, including beliefs about the inquiry teaching approach (e.g. Crawford, 2007; Fletcher & Luft, 2011; Wallace & Kang, 2004), nature of science (e.g. Abell & Smith, 1994; Brickhouse, 1990; Lederman 1999; Tobin & McRobbie, 1997), science teaching and learning (e.g. Bryan, 2003; Hancock & Gallard, 2004; Levitt, 2002; Tsai, 2002), and self-efficacy (e.g. Brouwers & Tomic,
2000; Ramey-Gassert & Shroyer, 1992; Enochs, Scharmann, & Riggs, 1995). In this study, we investigated teachers’ educational beliefs about the three-dimension approach proposed by the new science education reform. Specifically, we studied prospective middle-school teachers’ beliefs about teaching and learning science by integrating scientific practices, crosscutting concepts, and disciplinary core ideas in their instructions.

Beliefs are inextricably entangled with knowledge (Pajares, 1992). Although scholars have made great efforts to define and delimit them, there is no agreement on their relationship. For instance, Nisbett and Ross (1980) viewed belief as part of human’s generic knowledge, whereas Kagan (1992) argued that knowledge is a kind of belief that has been confirmed to be true. Nespor (1987) held that beliefs play a more important role in people’s decision-making than knowledge. While Roehler, Duffy, Herrmann, Conley, and Johnson (1988) argued that knowledge is more influential than belief. Although scholars held different views about the relationship between knowledge and belief, almost all of them agree that knowledge and belief are interwoven. One cannot study teacher beliefs without considering a teacher’s knowledge, since what one believes to be true is usually based on what one knows about a subject. For instance, science teachers’ educational beliefs rely on their understanding of science, perception of effective teaching, and knowledge about students. In this study, we investigated prospective middle-school teachers’ beliefs development about the three-dimension approach by examining their knowledge acquisition process in the methods course.

Teachers’ beliefs are clustered, complex, and multifaceted which should be regarded as an integrated system rather than isolated ones (Bryan, 2003; Fives & Buehl, 2012). In 1968, Rokeach defined the concept of belief system and pointed out the embedded nature of beliefs. That is, people hold countless beliefs which are different in their intensity and power. Some
beliefs are in the central of belief system while others are more peripheral. The central beliefs are more resistant to change compared with the peripheral ones. Pajares (1992) suggested that “Belief substructures, such as educational beliefs, must be understood in terms of their connections not only to each other but also to other, perhaps more central beliefs in the system” (p. 325). Therefore, prospective teachers’ beliefs about the three-dimension approach should be investigated by considering not only the knowledge that they gained in the methods course, but also the influence from teachers’ other beliefs in their belief systems, such as teachers’ beliefs about self, students, and environment.

Although one of the original purposes of belief research was to establish a conceptual construct that could be used to explain and predict the difference of teachers’ practices (Fives & Buehl, 2012), the relationship between teachers’ beliefs and practices is far more complicated than it was expected to be. Scholars reported very different results about how teacher beliefs relate to their practices. Specifically, some scholars (e.g. Aguirre, Haggerty, & Linder, 1990; Bencze, Bowen, & Alsop, 2006; Beswick, 2005; Cronin, 1991; Haney, Czerniak, & Lumpe, 1996; Hashweh, 1996; Laplante, 1997; Mitchell & Hegde, 2007) found that what a teacher believes is a good indicator of their actions while others (e.g. Boz & Uzuntiryaki, 2006; Hancock & Gallard, 2004; Kang & Wallace, 2004; Lee, Baik, & Charlesworth, 2006; Mellado, 1998; Stipek & Byler, 1997) reported that teachers’ beliefs were not necessarily consistent with their classroom practices. The widely accepted interpretation is that the investigated belief is only one of the factors that influence teachers’ practices. Besides the investigated belief, there are many other factors that support or impede the enactment of teacher beliefs (Five & Buehl, 2012). Some of these factors are internal ones, like teachers’ knowledge (Akcay, 2007), competing beliefs in their belief systems (Sztajn, 2003), and identity (Enyedy, Goldberg, & Welsh, 2006). Others are
external factors, such as the required curriculum and test (Lim & Chai, 2008), school culture (Barkatsas & Malone, 2005), colleagues (McMullen et al., 2006), administrative demands (Maxion, 1996), and mentor teachers (Crawford, 2007). Teacher’s actual practices are the result of the interactions of teachers’ beliefs as well as many internal and external factors.

Methods

Research Design

A multiple-case design (Yin, 2014) was used in this study. Teacher beliefs have always been regarded as a “messy construct” (Pajares, 1992). The case study approach can help reveal the complex developing process of prospective teachers’ beliefs and the complicated factors influencing their belief enactment by providing researchers with a deep understanding of the problems since it can cover “both a particular phenomenon and the context within which the phenomenon is occurring” (Yin, 1993, p. 31).

The Four Prospective Teachers as Participants

This study employed the maximum variation sampling strategy (Patton, 2002) to select four prospective teachers from the methods class as our participants. They were Kate, Mike, Mary, and Sally. Among the participants, Kate, Mike, and Mary were juniors and Sally was a graduate student. In practicum, Kate taught a 7th grade life science class. Mary taught an 8th grade physical science class. Mike and Sally taught 6th grade earth science classes. All participants were in their twenties and majored in middle grades education.

Data Collection and Analysis

Case study is a detailed investigation, “often with data collected over a period of time, of phenomena, within their context” (Hartley, 2004, p. 323). The data of this study included: (1) pre-questionnaire which were used to determine prospective teachers’ initial knowledge and
beliefs about the three-dimension approach at the beginning of the semester; (2) three reflections written by prospective teachers during the semester to record their thoughts, feelings, and insights by reflecting on the three learning stage; (3) post-questionnaire which aimed to exam prospective teachers’ belief development process and their ending beliefs about the three-dimension approach; (4) researchers’ journals documenting classroom observations, class discussions, and numerous informal conversations with prospective teachers during the whole semester; (5) in-depth semi-structured interviews about prospective teachers’ learning experience in the methods course, as well as their experiences, thoughts, and practices related to the three-dimension approach in practicums, recorded by using a digital audio recorder.

All interviews were fully transcribed by the first author. Then, a database was built for each participant by arranging their pre-questionnaire, reflections, post-questionnaire, and interviews chronologically. The researchers’ journals were also sorted and added to each participant’s file. Then, the inductive method (Erickson, 1986) and the cross-case analysis technique (Yin, 2014) were used to analyze the data. The inductive approach allowed prospective teachers’ beliefs about the three-dimension approach and factors influenced their belief development and enactment to emerge from data. The cross-case technique helped in finding the similarities and differences across the multiple cases.

The data analysis consisted of four steps. First, for the belief development part, researchers read and reread the database of participants to get a general idea of each participant’s belief development process. Then, data were coded from a teaching and learning perspective, including participants’ beliefs of teaching and learning science via the three-dimension approach, as well as the factors influencing their belief development. Researchers started by first coding data from Mary’s case. Then, the emerging codes from Mary’s case were used to analyze the
other three participants’ database. During this process, new codes emerged and existing codes were modified, deleted, or combined until a completed coding scheme was developed. In an effort to track participants’ belief development process, researchers created a belief development matrix for each participant, based on data analysis (See Table 4.1 for example). Second, for the belief enactment part, participants’ interviews and researchers’ journals were scrutinized to ascertain participants’ intentions and practices related to the three-dimension approach in their practicums. Participants’ questionnaires and reflections were used as references to triangulate our data analysis in this step. Codes form three perspectives were created, including participants’ intentions, practices, and factors’ influencing beliefs enactment. The coding process started from Mary and was refined by coding other cases. Third, the themes about participants’ beliefs development and enactment related to the three-dimension approach emerged from the first two steps were synthesized into the profile of each participant. Finally, the four cases were compared to identify any similarities and differences across the cases.

Table 4.1:

Belief Development Matrix for Sally

<table>
<thead>
<tr>
<th></th>
<th>Pre-stage</th>
<th>1st stage</th>
<th>2nd stage</th>
<th>3rd stage</th>
<th>Post-stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Teaching-P</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Teaching-NU</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Teaching-NG</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Learning-P</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Learning-NU</td>
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<td></td>
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<tr>
<td>Learning-NG</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>None</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: P, NU and NG stands for positive, neutral, and negative beliefs about teaching and learning the three-dimension approach; None stands for no evidence about beliefs
Role of Researchers

The second author served as the primary instructor of the methods course and the first author served as her teaching assistant. Given that “the researcher is the instrument” for qualitative research (Patton, 2002), our insider statuses could help us develop a holistic and deep understanding about the context of this study. However, on the other hand, this might also bring some bias to this study. Therefore, some measures were taken to improve the quality of the study.

Validity and Reliability

Validity and reliability are important for a good qualitative research (Patton, 2002). In this study, we employed three strategies suggested by Creswell (2013) to improve the validity, including (a) triangulation of the data through questionnaires, reflections, interview, and researchers’ journals; (b) rich description of each case to build a complete picture of the study; (c) member checking with all participants by sending them their profiles after their cases were constructed to improve fidelity of the study. In addition, we used case study protocol and case study database --the two tactics proposed by Yin (2014) to ensure the reliability of the study.

Results

The pre-questionnaire indicated that the four participants had never heard about the three dimensions before entering the methods course. Therefore, these participants had no obvious knowledge and identifiable beliefs about the three-dimension approach at the beginning of the semester.

Kate’s profile: It benefits teaching and learning

When instructors first introduced the three dimensions, Kate perceived them to be complicated. “The new science education reform seems very complex with both the New K-12
Science Education Framework and the Next Generation Science Standards (NGSS). When we saw the layout of the three dimensions (in NGSS), I was really impressed’’ (Reflection #1).

However, Kate was a prospective teacher who had great passion for education and was open to new teaching methods. In her first reflection, she wrote, “I really feel like I am beginning to learn the important features of teaching in this methods class. I am so excited for my teaching career and getting to incorporate the three dimensions in it!”

Kate’s knowledge about the three-dimension approach was developed by doing the four classroom projects in the second learning stage. She started to realize the connections among the three dimensions. “The three dimensions overlap a lot so it is hard to differentiate them completely, but I guess that actually makes it (integration) easier! I really like this standard and these activities. The three dimensions really help to explain one another in a way” (Reflection #2). Based on her knowledge about the relationship of the three dimensions, Kate thought that the three dimensions could work together to facilitate science learning.

Students need each one (dimension) to help understand the others… For example, in the Fossil Finder project, by analyzing the data, understanding the evidence of common ancestry, and actually seeing the patterns through images the students can learn concept very easily! I truly think that the integration of these three dimensions benefits students because without one of these three dimensions or just teaching them individually will make it more difficult for the students to completely understand. The students can’t analyze the data without actually seeing images of how the structure and traits of these species evolved. (Reflection #2)
Kate’s positive belief about the three-dimension approach was further developed in the third stage. She not only emphasized the significance of the approach for students’ learning, but also thought it should be feasible in science classrooms.

The three dimensions were really important to recognize and use so it could be good to use for them (students)! The earlier they learn the skills, the better it will be for them! Integrating these together makes the learning more complex, but as long as you keep it in their range of understanding and ability then they (students) should use it successfully! It helps to build their learning and not just basic checking for understanding which is very important when preparing for high school science. (Reflection #3)

Kate also thought that the three-dimension approach could help teachers design instructions. Kate said that she liked NGSS and its three-dimension approach because “they not only tell teachers the goal—performance expectations, but also show teachers the three specific directions to go” and this “makes it much easier for the teacher to know what to teach when trying to achieve a certain performance standard” (Researcher Journal).

With more knowledge of the three dimensions, Kate’ confidence was also improved during the semester. At the end of the semester, Kate felt that the three-dimension approach was easier than she had expected. “I was really afraid of them at first, but now I’m not. It’s still hard sometimes to figure out how to integrate them, but I know strategies on how to do it now!” (Post-questionnaire). For teachers, Kate thought that, at first, the three-dimension approach might cost extra efforts. But, after they were used to it and collaborated together, it would not be very time consuming.

Initially, integrating three dimensions may take extra time and efforts to build lessons. I think it would take teachers a bit of time to practice using it...But after a while, by
planning lessons with fellow teachers, I think it could go well. (Interview, November 15, 2013)

Despite her positive beliefs, Kate did not attempt to use the three-dimension approach to teach her students science in her practicum. In the interview, Kate said that she was in a really well-disciplined school and students were intelligent kids. So, if she presented the three dimensions to them, they could take it well. However, although Kate really wanted to try it in classroom teaching, she gave it up eventually. First, Kate felt that she was not sure about the actual effect of the approach, since she had never seen it was implemented in real classrooms. “I just really don’t know how well it will work until I can actually see it works” (Interview, November 15, 2013). Second, she felt that she had no right to use the new teaching method because her practicum school was not using NGSS and her mentor teacher didn’t even know about the three dimensions.

I just feel like if she (mentor teacher) weren’t using it, then they (schools) didn’t think it was necessary….I have thought about how to use it (the three-dimension approach). But, I didn’t use it in her class because I didn’t think I had the right to teach them (students) something that I wasn’t supposed to teach them. (Interview, November 15, 2013)

**Mike’s profile: It has both pros and cons**

Mike had mixed feelings about using the three-dimension approach from the beginning. On the one hand, he liked the three dimensions and thought that the new approach should be “a great way to incorporate multiple concepts” (Reflection #1). On the other hand, Mike found that he could not fully understand the three dimensions and had no idea of how to integrate them. “I do not fully understand them (the three dimensions) and I’m still not quite sure how this all
works” (Reflection #1). Due to his mixed feelings, Mike seemed to be ambivalent. He thought that the three-dimension approach was likely a good teaching method. However, he also worried that the three dimensions would be too much for students and teachers, because he found it was not easy to understand them. “The idea of it (integrating three dimensions) sounds nice” However, “when focus is spent on combining multiple subject matters, it may be hard for students to actually retain what they are supposed to” and “how much of a burden would they be on a teacher to create and implement on top of all of the other duties” (Reflection #1).

Mike’s knowledge developed rapidly when doing the four projects in the second stage. He could not only identify all the three dimensions involved in the projects, but was able to also understand how the dimensions connected with each other. For instance, when reflecting on how to achieve the performance expectation MS-ESS1-1 “Develop and use a model of the Earth-sun-moon system to describe the cyclic patterns of lunar phases” in the Moon Project, he wrote,

Science practices can be demonstrated through building a model…I think the model used for science practices will be beneficial in incorporating disciplinary core ideas. When trying to integrate crosscutting concepts, we can use the pattern of the moon’s location to predict where it will be in the sky. (Reflection #2)

With the growth of knowledge, Mike’s confidence also seemed to be increased. When reflecting on his learning experience. He mentioned “I don’t think I ran into any difficulties integrating the three dimensions” and “I am confident in my ability to integrate the dimensions because we have had a lot of practice with them and it doesn’t really seem hard to do such” (Reflection #2). Moreover, Mike started to realize the benefits of the three dimensions. He said that “crosscutting concepts could help students see the connections of their knowledge” and
“practice dimension is good because hands-on activities are always great for students’ learning” (Researcher Journal).

Although Mike’s knowledge and confidence grew rapidly, he thought that designing lesson plans via the three-dimension approach was complicated because he needed to consider three dimensions and weave them logically. “When I wrote lesson plans, I noticed that one dimension has a huge influence on another dimension and how that dimension was placed” (Interview, November 18, 2013). Therefore, although Mike believed the three dimensions were conducive to students’ science learning “because in the long run it connects students to some material and instruction they may not have gotten just from the learning contents” (Reflection #3), he was also concerned that the three-dimension approach would put a lot of extra work on teachers.

At the end of the methods course, Mike held mixed beliefs about the three-dimension approach and believed that it had both pros and cons. For science learning, on the one hand, Mike thought, “The three dimensions benefit students in a way that it touches more and be able to polish students’ different sets of content skills all at once”. (Interview, November 18, 2013). On the other hand, Mike worried that students might not be able to comprehend too much knowledge at the same time. For science teaching, Mike thought the three dimensions were useful guidelines for teachers to design their lesson plans. “NGSS provide you with the perspectives and strategies of teaching those concepts and topics” and “Integrating three dimensions makes it better to connect different area of science and other disciplinary areas to enhance your lessons” (Interview, November 18, 2013). However, at the same time, Mike also believed that compared with traditional teaching which mainly focused on content knowledge, the three-dimension approach, “may bring a little bit more work on teachers” since teachers need
to incorporate three aspects simultaneously and consider how to connect them reasonably when creating lesson plans. In addition, “although the three dimensions give you the guide to teach, they also take away your freedom to create your lesson plans” (Interview, November 18, 2013).

Because of his worries and the difficulties he met in reality, Mike did not use the three-dimension approach it in his practicum; although, he had thought about it. In informal conversation, Mike mentioned the following reasons for not actually using it. First, he had to focus more on content knowledge because students needed to pass district tests. Second, he had to teach by following his mentor teachers’ thoughts. Unfortunately, his mentor teacher had never heard of NGSS and he did not anticipate the state was going to adopt it, either.

I felt that when I was teaching in class, I was trying to teach more contents because students need to pass their tests. I thought about it (using the three-dimension approach). But I didn’t do it, especially when you work with other teachers and they wanted you to include certain things. When I was planning my activities, the mentor teachers would tell me what he wanted to teach. Then, I would try to do the things that he approved.

(Researcher Journal)

Third, teaching time was limited. His mentor teacher was very busy, even though he mainly focused on content knowledge in his teaching. Therefore, Mike did not think he had enough time to teach science from three different perspectives. Finally, because not many school teachers understood and used the three-dimension approach, there was almost no colleague with whom Mike could collaborate

Mary’s profile: It’s just too much

Mary’s beliefs about the three-dimension approach appeared to be mainly negative. When she first encountered the three dimensions in NGSS, she perceived they were so
complicated that she could not even figure out how to read them. “The charts and colors of the three dimensions in NGSS look overwhelming and complicated. I probably would not have been able to compute the standards if the instructors had not explained what to look for”, “I am not quite sure what the standards are explicitly looking for”, and “I am not confident in interpreting the standard” (Reflection #1). In informal conversation, Mary even asked instructors why they needed to learn the three-dimension method since NGSS was not used in local schools.

In the second stage, even though most of time Mary could identify the three dimensions involved in the four projects and understand how they connected, she still thought the three-dimension method was a confusing idea. She wondered why she needed to integrate the three dimensions since they already interwove in activity.

The word “integrate” means to weave it to a lesson plan. When we did the four projects, it seemed that all, the crosscutting concepts, disciplinary core ideas, and practices, seemed to be already there. I was confused….When I saw it was already in the activity. There was one question was like how you integrate it. My answer was that it was already being integrated. So, why would I want to integrate it again? (Interview, November 20, 2013)

In the last stage, Mary was still not confident in herself. Although her unit plans showed that she was able to design lesson plans by integrating the three dimensions, she attributed it to her good luck rather than her ability.

This lesson plan was set up to be able to address all three dimensions…I think that I just got lucky in being able to recognize and apply the three dimensions to my lesson plans after I wrote them, but if I had another standard or another unit plan I don’t know how well I will be able to integrate the three dimensions. (Reflection #3)
At the end of the semester, Mary still believed that the three-dimension approach was too complex and contained too much content. “In one standard there are three dimensions that need to be integrated into the lesson and each dimension could be a lesson of its own…they are very content heavy themselves” (Post-questionnaire). “When you look at NGSS, it is like one, two, and three. Here is A, oh, here is another A. There is B, there is B too. So, it was really complex and could have been simple… I was really confused and overwhelmed (Interview, November 20, 2013). Because of the complexity of the three-dimension approach and her experience in practicum, Mary believed that the three dimensions were too much for both teaching and learning. Specifically, Mary believed that teachers had no time to design their lessons by following so complicated teaching approach.

It will take a lot of effort and time that teachers don’t have. In my practicum classroom, my mentor teacher barely had time to sit down because he was always changed his lesson plans, he was going to meetings, and he was calling parents… I think that is a real teacher needs to do. If we bog down with this NGSS, three parts in one standard, it’s too much. (Interview, November 20, 2013)

Moreover, Mary believed that assigning too much time to the three dimensions would distract teachers’ attention from helping students build their knowledge foundations.

If you go with the NGSS and three dimensions, there are a lot of aspects. They might not even give you the time to be able to build the foundation you kids need. You don’t have enough time. It doesn’t become priority to scaffold your kids some physics concepts for astronomy because you are so focusing on three dimensions of the standards. (Interview, November 20, 2013)
Similarly, Mary thought that the three-dimension approach was not conducive to learning because it was too much for her students to handle.

It might be so overwhelming to the kids. You can’t just blow their minds. If students are being taught something that they didn’t understand and teachers keep going on and on, students will turn off their minds… You need to give them the time to swallow and digest. I can’t let my kids just sit and saturate information. (Interview, November 20, 2013)

Moreover, Mary stated that many prospective teachers in the methods course disliked the three-dimension approach. This influenced her attitudes towards it.

I don’t think I met one person who thought it (the three-dimension approach) was beneficial in the classroom and anyone who fully understood it. I think a lot of us were on the same page. It was too much… It influenced me. It refers to what I am thinking. So, I am not alone. (Interview, November 20, 2013)

When designing her lesson plans for practicum, Mary said that, the three dimensions were “not even in the back of my mind” because she “didn’t mean to do it” (Interview, November 20, 2013). She gave the following reasons. First, she thought that the three dimensions were too complicated and they only work in ideal classroom. “We were in the fictitious classroom teaching fictitious kids and everything moves smoothly…I thought that it will work in ideal classroom. You could integrate all of these things. But, we never saw it in a (real) lesson plan” (Interview, November 20, 2013). Second, she was very uncomfortable and unconfident about the three-dimension approach.

I don’t understand it. It confuses me. As a teacher, I can’t image how I can teach what I
feel confused to kids… I need to feel confident in what I am teaching. I need to know the material inside and out in order to clearly express to the kids. I think it is really important to know what you are talking about because I have so much insecurity and questions. I am not confident in this. I won’t be able to teach in my classroom. (Interview, November 20, 2013)

Third, her mentor teacher had never heard of NGSS and its three-dimension approach. “He was a real classroom teacher. The fact that he even never heard of NGSS made me think, “why do I need to know and teach it” (Interview, November 20, 2013). Moreover, Mary believed that NGSS would never be implemented by the state. So, it is not necessary to learn and use it at all. “Some classmates said that the state is goanna adopt it. But, it will not be implemented because teachers are not goanna want to change it” (Interview, November 20, 2013).

**Sally’s profile: I want to be a specialist of it**

Although Sally was a graduate student, she still felt confused when she first encountered the three dimensions in NGSS. “Originally, I was confused, was not clear about what’s going on, a little overwhelmed” (Interview, November 22, 2013). Because of the complication of the three dimensions, Sally thought that integrating the three dimensions was not easy and suspected its feasibility. “Integrating all of the three dimensions requires a great deal of creativity” and “it is a generally good idea, however, with the amount of time we have with the students, the amount of content we have to cover in general, and the high number of students to teachers, it is not very realistic” (Reflection #1). However, Sally did not close the door to this new teaching approach. “It is difficult to incorporate all three dimensions, but I believe with some creativity and a deep understanding of the content, it is possible” (Reflection #1).
In the second learning stage, Sally was still uncomfortable about the three-dimension approach. In informal conversation, she said that crosscutting concepts are easier to be incorporated compared with the other two dimensions because they are broad and the other two are abstract. In addition, she could only integrate two of the three dimensions. It was not easy to integrate all the three. Due to her insufficient knowledge, Sally’s beliefs about the three-dimension approach at this time were primarily negative. “Most of time, I feel the three dimensions are extra work for teachers that would not make much difference in my lesson plans” (Reflection #2).

Things started to change in the third learning stage. Sally’s knowledge and confidence seemed to increase greatly when she designed unit plans. In her unit plan “Rocks and Minerals”, Sally not only showed her ability to design lesson plans via the three-dimension approach, but also discussed how each set of crosscutting concepts could relate to the activities in her lessons. Sally said the following words to describe her feelings.

When it was towards the end of the semester, I kind of got the big picture of NGSS...
When I did the mini unit project, it made sense to me. When I had to actually put them (three dimensions) together in a lesson or a unit, that’s when it made sense. So, it is kind of build, build, build. Then, OK, got it! So, at first, nothing, confused, overwhelmed. At the end, I felt very confident. (Interview, November 22, 2013)

At the end of the semester, Sally’s beliefs about teaching science via the three-dimension approach also seemed to become mainly positive. She thought that after teachers were used to the new teaching method, it would not cost extra efforts. “At first, it has some extra work. Afterwards, it will become a kind of natural” (Interview, November 22, 2013). Moreover, Sally
believed that the three dimensions could guide lesson planning by showing the connections of ideas.

The three dimensions scaffold lesson planning... The three dimensions make all of these coherent and put them being a big picture, like puzzle pieces. Three dimensions connect everything...They help teachers to see that connections...

My attitudes change a lot. When we did the mini unit to include them, that’s when I saw the extra work does make big differences... It will make me a much much better teacher. (Interview, November 22, 2013)

Sally thought the three dimensions would help teachers and students alike. “Over the course of the entire school year ‘integrating the three dimensions’ will be conducive to middle school students’ science learning because it will help them to see connections, the role of the scientific method, and more” (post-questionnaire).

When talking about her practicum during the interview, Sally said that she had asked her mentor teacher about NGSS. Her mentor teacher said they did not use it yet. But, they would do it eventually when it was common. Sally said that her mentor teacher was very supportive. He would encourage her to try the three-dimension approach if she wanted to do it in classroom. Moreover, she really enjoyed helping students learn science from three different perspectives. However, although Sally had thought about trying the three-dimension approach, she didn’t really use it in her practicum because she thought she was still learning about it and she did not feel fully confident. “If I had this methods class before the practicum, I would have integrated it. But, I was still learning it. I didn’t want to bring it when I didn’t really know about it”. (Interview, November 22, 2013)
facts that there were very few example lesson plans available online and she had never seen a class room teacher used the three-dimension approach to teach science also made her feel unsure about her ability to do it.

Looking back on her learning experience about the three-dimension approach, Sally said some undergraduates’ negative feelings about the three-dimension approach actually motivated her. As a graduate student, she should work hard to master complicated new teaching methods.

They (undergraduates) probably motivate me to try even harder because some of them said “I don’t want to do it, this is too hard”…Being in graduate school, I am doing my Master degree… You need to study hard to be an intelligent thinker, a specialist who brings all of these new ideas. It definitely made me work harder. (Interview, November 22, 2013)

Moreover, Sally said that she liked to catch up with the new reform. “I think probably in five or six years, it (the three-dimension approach) will probably be a big deal” (Interview, November 22, 2013).

**Discussions**

This study provided evidence that participants’ belief development about the three-dimension approach is a complex process involving many factors. These factors included their knowledge about the approach, learning experience of the approach, openness to new teaching methods, other beliefs in their belief systems, and the influence from peers. Specifically, participants’ beliefs about the three-dimension approach were based on their understanding of it. With the growth of their knowledge about the approach, participants developed more and more beliefs about it. Participants’ personal learning experience of the approach also shaped their
beliefs about it. They believed the three-dimension approach was too much for their own students to handle, if they themselves could not fully understand it. These prospective teachers worried the approach would put an extra load on teachers, if they felt that designing lessons by integrating the three dimensions was complicated work. Participants’ openness to new teaching methods was also important for their belief development. When first facing the complicated three dimensions, Kate, Mike, and Sally were open to them, whereas Mary resisted them and started to develop negative beliefs. In addition, peers’ attitudes toward the three-dimension approach also played a role in participants’ belief development. For instance, classmates’ negative words and attitudes toward the three-dimension approach contributed to Mary’s “useless” beliefs about it. Yet, some undergraduates’ complaints about the difficulty of the three-dimension approach actually motivated Sally to work harder on it. Finally, participants’ other beliefs, such as beliefs about self (e.g. sense of efficacy, self-expectation, teachers’ role in curriculum implementation), beliefs about students (e.g. students’ ability, students’ learning), and beliefs about context (e.g. mentor teachers’ attitudes, limited time in real classroom, expectation of NGSS implementation, etc.), also affected their belief development. For instance, Mary’s low sense of self-confidence, beliefs about students’ insufficient ability and characteristics of learning, mentor teachers’ neglect of NGSS, and limited time in real classroom contributed to her negative beliefs about the three-dimension approach. In contrast, the high self-expectation, supportive mentor teacher, and optimistic attitude towards the implementation of NGSS helped Sally develop her positive beliefs.

At the end of the semester, participants changed or enhanced their beliefs about the three-dimension approach. Specifically, Kate and Sally believed that the approach would benefit science teaching and learning by scaffolding lesson planning, promoting students’ deep
understanding, as well as helping students see connections between knowledge and learn scientific methods. Although teachers need time to learn and practice how to integrate three dimensions, it would not put extra load on teachers after they were used to the approach. On the contrary, Mary’s beliefs about the approach were totally negative. She thought that the three dimensions were too much for teaching and learning. She believed classroom teachers had no time and energy to use such a complicated method to design their lessons and students would not be able to digest all three dimensions. Unlike the other participants, Mike believed that the approach had both pros and cons. He agreed that the three-dimension approach could benefit learning and guide teaching. Meanwhile, he also worried that it would be too much for students, require extra efforts from teachers, and constrain teachers’ creativity.

Due to different beliefs about the three-dimension approach, participants had different intentions of using it in their practicums. Specifically, Kate, Mike, and Sally had thought about trying the approach in their practicum because they believed that it could benefit teaching and learning. Whereas, the three-dimension approach were not even in the back of Mary’s mind when she designed her lesson plans for practicum teaching. However, despite participants’ intentions of using the approach were different, none of them really used it in their practicum because their planned instruction was influenced not only by their beliefs about the three-dimension approach, but also by other beliefs in their belief system (e.g. sense of self-efficacy, expectations of NGSS implementation), and many contextual factors (e.g. predominant state standards, mentor teachers’ attitudes, high-stake tests, available resources, etc.). For instance, Mary did not use the three-dimension approach, not only because of her negative beliefs about it, but also because of her low sense of self-confidence, pessimistic expectations of NGSS implementation, the constrains from the predominant old state standards, and mentor teachers’
neglect of NGSS. Although Sally held positive beliefs about the approach and was assigned to a supportive mentor teacher, she did not really try it, perhaps because of her low sense of self-efficacy of using it and few available resource.

**Conclusions and Implications**

In this study, we examined four prospective middle-school teachers’ beliefs, intentions, and practices related to the three-dimension approach proposed by the new science education reform. The conclusions and their implications for the field of science teacher education are discussed as follows.

First, a typical science teaching methods course can be a viable setting for helping prospective middle-school teachers develop beliefs about the three-dimension approach by providing them with knowledge and learning experience about it, as well as peer influence. In this study, prior to taking the methods course, participants had no obvious beliefs about the three-dimension approach, since they had never heard of it before. At the end of the semester, participants developed their own beliefs about it. However, the present study also suggested that prospective teachers’ beliefs about the three-dimension approach was affected not only by the methods course, but also by their openness to new teaching methods and other beliefs in their belief systems. Therefore, teacher educators need to pay attention to all involved factors, rather than only factors associated with the methods course. The more the factors align with each other, the more strongly prospective teachers’ beliefs about the new three-dimension approach develop. For instance, science teacher educators could help prospective teachers become more open to the three-dimension method by explaining the rationales and advantages of it. By providing prospective teachers with more practice opportunities and encouragement, teacher educators
could help prospective teachers gain a good learning experience of the three-dimension approach and improve their sense of self-efficacy of using it. In order to create a favorable atmosphere, teacher educators could ask some prospective teachers to share their positive beliefs about the three-dimension approach in class.

Second, although prospective teachers acknowledged the benefits of the three-dimension approach, they also worried about the difficulty of implementing it. Specifically, these new teachers believed that while incorporating the three dimensions might enhance science teaching, it will also require teachers to spend more time and effort in planning lessons since they need to consider three dimensions simultaneously and think about how to connect them reasonably; while learning science from three different perspectives could help students deepen their understanding, it may also set higher demands on students’ learning ability. This is not surprising considering that every coin has two sides. While incorporating more aspects may bring science education more benefits, it is also more challenging than traditional approach of science teaching and learning. Given that integrating disciplinary ideas and inquiry practices is difficult in itself for teachers (Chiapetta & Adams, 2000; Minstrell & van Zee, 2000), it is likely more difficult to incorporate the NGSS three dimensions. This is especially true for prospective teachers who are just starting to learn how to plan and carry out lessons. Therefore, science teacher educators should give prospective teachers ample time to comprehend the three dimensions gradually, experience the integrations of the three dimensions personally, and practice how to use the three-dimension approach to plan lessons frequently. This would help prospective teachers develop their knowledge of the three-dimension approach, enhance their abilities of integrating three dimensions, and improve their self-efficacy of using the approach to promote students’ science learning.
Third, prospective teachers’ beliefs about the three-dimension approach were just emerging in this study and needed to be further cultivated. Teacher beliefs “can only be inferred from a collective understanding of what human beings say, intend, and do” (Pajares, 1992, p. 316). Therefore, when investigating teachers’ beliefs, researchers should not only study teachers’ espoused beliefs, but also infer them from teachers’ intentions and practices. In this study, although some participants claimed that they had positive beliefs about the three-dimension approach and wanted to try it, they didn’t really use it in their practicums. This, to some extent, indicated that prospective teachers’ positive beliefs about the three-dimension approach were still tentative and need to be further cultivated. This is not surprising considering that participants did not even get chance to see how the three-dimension approach could be used to teach science in real classrooms. Consequently, even those participants who held positive beliefs about the approach were not very sure about the actual effect on their students’ learning. This suggested that a methods course devoid of connecting with real classroom teaching practices can only play a limited role in developing prospective teachers’ beliefs about the three-dimension approach. Teacher educators should introduce the three-dimension approach prior to the practicum experience, if possible. For instance, teacher educators could show prospective teachers some classroom videos, giving real images of how in-service teachers teach science by integrating the three dimensions. They could also invite some in-service teachers who are willing to try the new teaching approach in their classrooms to be guest speakers to introduce their experience, insights, and expertise of using the three-dimension approach, as well as the feedbacks from students. Finally, literature indicates that some research (e.g. Bencze, Bowen, & Alsop, 2006; Beswick, 2005; Cronin, 1991; Mitchell & Hegde, 2007) indicated that what a teacher believes is a good indicator of their actions; while other research (e.g. Boz & Uzuntiryaki, 2006; Hancock
& Gallard, 2004; Kang & Wallace, 2004; Lee, Baik, & Charlesworth, 2006) reported that teachers’ beliefs were not necessarily consistent with their classroom practices. This study echoed these literatures. For instance, Kate and Sally’s practices were inconsistent with their positive beliefs about the three-dimensional teaching approach, while Mary’s practice was consistent with her negative beliefs about the approach. This is because a prospective teacher’s belief enactment was influenced not only by a new teacher’s beliefs about the three-dimension approach, but also by other beliefs in his or her belief systems and contextual factors. Considering that prospective teachers’ positive beliefs developing from a methods course are tentative, there is high probability that other beliefs in their belief system and contextual constraints will override the effects of their positive beliefs about the three-dimension approach. This proved to be especially true in the current situation. At present, the science education reform needs carefully developed methods courses that prepare prospective teachers for understanding and using the new three-dimension approach. On the one hand, the National Science Teachers Association (NSTA) emphasizes use of the three dimension approach, by stating, “Even if your state does not adopt, the NGSS represents good practices in science education and should be embraced by all science educators” and “Studying the standards can help you improve your teaching and learning regardless of when (or even whether) your state adopts the NGSS” (“FAQ on NGSS”, 2013). On the other hand, many states have not adopted the NGSS and do not intend to use the new science standards. This presents many contextual constraints for prospective teachers to practice the new three-dimension approach. For instance, in this study there were multiple obstacles: no practicum school had begun using NGSS and its three-dimension approach; mentor teachers had never heard about NGSS or just ignored it; prospective teachers could not find colleagues to collaborate; and, there are currently few
resources available online. All these real problems prevented these prospective teachers from trying out and practicing the new three-dimension approach. Furthermore, the adverse contextual factors could also impede prospective teachers’ practices by influencing their beliefs in their belief systems. For instance, prospective teachers felt unsure about the actual effects of the three-dimension approach, since they did not get chance to see how it could be used in real classrooms. Because prospective teachers had no opportunity to practice the three-dimension approach in classrooms, their sense of self-efficacy was inadequate. In order to counteract the adverse effects from contextual constraints, a lot of efforts are needed. For instance, teacher educators could do more research about the new three-dimension approach and come up with some practical strategies to inspire prospective teachers. Educational websites could provide lesson plans and classroom videos to show examples of integrating the three dimensions in science classrooms. Furthermore, teachers might participate in virtual communities where teachers could share their experiences and insights of using the new teaching approach.
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CHAPTER 5
CONCLUSIONS AND DISCUSSIONS

Conclusions

The new K-12 Science Education Framework (NRC, 2012) and Next Generation Science Standards [NGSS] (2013) bring many new challenges for science educators. The three studies in this dissertation shows that prospective middle-school teachers have limited knowledge of engineering design and its teaching, need help about teaching crosscutting concepts, and know almost nothing about the three-dimensional teaching approach. However, although the new tasks proposed by NGSS are challenging, these studies show promise in that overcoming them is not impossible. There are possible ways to help teachers, especially middle-school prospective teachers, develop their knowledge about engineering design and its teaching, learn how to teach crosscutting concepts, and integrate the three dimensions of NGSS in science instructions.

Experience is important for teachers’ learning (Feiman-Nemser, 1983; Loucks-Horsley et al., 1998; Jeanpierre, Oberhauser, & Freeman, 2005). Science teachers need to have similar learning experience to their students before they can teach them (Loucks-Horsley et al., 1998). Therefore, in order to be able to teach engineering design effectively, science teachers themselves need to experience and learn engineering design first. Chapter 2 indicates that a methods course can help prospective middle-school teachers develop their knowledge about engineering design, insights of learning design, and strategies of teaching design by providing them with appropriate learning experience. Specifically, by engaging in design activity, prospective teachers’ understanding of engineering design improved. They expanded their
definition of engineering design, develop some understandings about the three core ideas proposed by NGSS, acquired design strategies, and made clear the relationship between science and engineering. Besides knowledge of engineering design, personal design experiences also help prospective teachers gain insights of learning design, such as identifying possible learning difficulties, foreseeing students’ feelings associated with the design process, and finding effective ways to facilitate design learning. The presentations and class discussion after design gave prospective teachers opportunity to share their experience and thoughts. Prospective teachers further developed their knowledge of engineering design and its learning by deepening their understanding, expanding their thoughts, and avoiding biased ideas. Designing lesson plans can provide prospective teachers with the opportunity to transform their knowledge of engineering design and its learning to pedagogical insights of teaching design, such as what difficulties that students may meet in design process, what strategies can be used to facilitate design learning, what factors should be considered when choosing design activities, and what principles should be followed to evaluate design learning.

Discipline-based science education can only provide students with discrete and fragmental knowledge and skills (Redish, Saul, & Steinberg, 1998; diSessa, 2002; Dreyfus et al., 2011). Crosscutting concepts can serve as the interdisciplinary bridge to connect various scientific areas, integrate STEM fields, and link science with other non-scientific areas as well as our daily lives (Gross & Fordham, 2011; Jin & Anderson, 2012). Chapter 3 suggests that the learning of crosscutting concepts is different from other concepts due to its interdisciplinary essence. Specifically, unlike learning other scientific ideas, students’ comprehension of crosscutting concepts includes not only common sense level and disciplinary level, but also interdisciplinary level. Therefore, the instructional objectives of crosscutting concepts should be
higher than other disciplinary ideas. In order to achieve the interdisciplinary-level objectives, science learning should break the boundaries among scientific areas and connect the crosscutting themes with students’ daily lives. Learning crosscutting concepts in various scientific areas give students the opportunity to comprehend the themes from different perspectives, foster the ability to integrate disciplinary scientific knowledge, and reason through problems crossing disciplinary boundaries. Applying crosscutting concepts in everyday scenarios can promote students’ interest of learning science and cultivate their scientific habit of minds. In addition, considering that crosscutting concepts are high-level constructs (Gross & Fordham, 2011) which are not easy to grasp, the learning of crosscutting concepts should be an incremental process through multiple learning cycles in various disciplinary contexts and everyday problem scenarios.

Integrating the Practice, Crosscutting Concepts, and Disciplinary Core ideas in science education is a new task proposed by NGSS. Chapter 4 indicates that a methods course can help prospective middle-school teachers develop their beliefs about the three-dimension approach by providing them with knowledge and learning experience about it. However, prospective teachers’ belief development is a complicated process which is affected not only by the factors from methods course, but also by their openness to new teaching methods and other beliefs in their belief systems (i.e. beliefs about self, beliefs about students, and beliefs about context). Therefore, in order to develop prospective teachers’ beliefs effectively, teacher educators need to pay attention to all involved factors and try to align them. The study also suggests that although prospective teachers can realize the benefits of the three-dimension approach, they also perceive it is difficult. This is not surprising given that even only integrating two dimensions—disciplinary ideas and inquiry practices is difficult for teachers (Chiapetta & Adams, 2000; Minstrell & van Zee, 2000). Moreover, prospective teachers are just starting to learn how to plan
lessons. However, despite the positive beliefs about the three-dimension approach and intentions of using it, no participants really try the new teaching methods in their practicum. This indicates that the positive beliefs developed from methods course are emerging which need to be further strengthened and the practices of the new three-dimension approach need continuous attention as new teachers travel on their journey to become reform-based science teachers.

**Implications**

Although the studies in this dissertation focus on prospective middle-school teachers, they may shed light on the big issue of how to prepare all prospective science teachers for the challenges from the new science education reform.

First, all prospective teachers need engineering design learning experiences. The study in Chapter 2 shows that prospective teachers may have very few, or even no prior design experience prior to entering a science methods course. Prospective teachers need design experience to help them understand knowledge of engineering design and give them the chance to go through students’ design learning. Without this necessary experience, prospective teachers’ knowledge development about engineering design and its learning will have to rely on rote memorization. In addition, in order to develop prospective teachers’ knowledge effectively, the design activity used in methods course should be carefully chosen and designed. Specifically, the design topic should be interesting for children and suitable for the grade level so that it can be used in prospective teachers’ future classrooms. The instructive objective of the design activity should target the core ideas and concepts proposed by NGSS so that it can help prospective teachers improve their knowledge of engineering design purposefully. Moreover, the implementation of the design activity should align with how it could be used in real classrooms.
so that it can be a teaching example for prospective teachers to refer. After design activity, prospective teachers need the opportunity to share and discuss their experience, problems, solutions, thoughts, and insights. This could help them expand their knowledge gained from one design activity and avoid biased ideas. Finally, prospective teachers need multiple and diverse design experience to help them develop a comprehensive understanding of engineering design and its teaching.

Second, prospective teachers need interdisciplinary learning experiences. Crosscutting concepts are important themes that not only repeat in scientific areas (AAAS, 1989), but also emerge in almost all other fields and even in our daily lives (Gross & Fordham, 2011; Jin & Anderson, 2012). The interdisciplinary essence of these themes means that the ultimate goal of teaching crosscutting concepts is to help students achieve its interdisciplinary-level rather than disciplinary-level understanding. In order to fulfill this requirement, science teachers need to possess extensive knowledge and the ability to analyze interdisciplinary problems. Therefore, science teachers need interdisciplinary education to help them expand their scientific knowledge and learn how to teach interdisciplinary topics. For example, prospective teachers, especially secondary prospective teachers who take discipline-based science courses, should be encouraged to take some content courses from other scientific or non-scientific fields. This will help prospective teachers broaden their subject matter knowledge. Prospective teachers might also take some interdisciplinary courses during their undergraduate experience, which could help them see the connections of the knowledge more deeply. In addition, teacher educators could bring some interdisciplinary topics into methods course. This may inspire prospective teachers to deal with the interdisciplinary part of teaching crosscutting concepts. Finally, prospective teachers should also pay attention to the examples of crosscutting concepts in our daily lives.
These examples would be helpful for prospective teachers to teach crosscutting concepts in their future science classrooms.

Third, prospective teachers need support from a methods course and contexts to help them learn and practice the three-dimension approach. Integrating three dimensions in science instruction is a new task proposed by NGSS. Prospective teachers may never heard about this component of the new reforms, before entering the methods course, not to mention having prior experience related to it. Science teacher educators have the responsibility to introduce this new teaching approach to methods course by improving prospective teachers’ knowledge about it and providing them with integration experience. Moreover, given that prospective teachers’ belief development about the three-dimension approach is affected not only by their learning experience from the methods course, but also by their openness to new teaching approach and other beliefs in their belief systems, teacher educators should also pay attention to these factors so that prospective teachers’ beliefs could be developed effectively. Besides methods course, prospective teachers’ learning about the three-dimension approach also needs supports from contexts. In Chapter 4, the four prospective teachers did not even get a chance to see how they might try to plan and teach using the three-dimension approach, because of the adverse contextual factors (e.g. state education department not adopting NGSS, practicum schools not using NGSS, mentor teachers not open to NGSS, no collaborative colleagues, few available resources about NGSS). This damages prospective teachers’ confidence in embracing a new teaching approach and developing self-confidence in using it.

**Future Directions**

This dissertation explores three contemporary challenges faced by middle-school prospective teachers related to the recent Next Generation Science Standards [NGSS]. Chapters
2-4 are only initial efforts in studying how to help prospective middle-school teachers develop knowledge about engineering design and its teaching crosscutting concepts effectively, and integrating the three dimensions of NGSS in science instruction. More work needs to be done to continue exploring how to prepare prospective teachers for the three new tasks in the future.

Chapter 2 focuses on prospective teachers’ knowledge of engineering design and its teaching developed in an university-based methods course. How to help prospective teachers transform their content knowledge of engineering design and pedagogical insights of teaching design gained from methods course into pedagogical content knowledge by interacting with students in real classrooms should be the future direction of the study. Chapter 3 establishes a model of teaching crosscutting concepts and provides a specific example of using it. Although the model seems to work pretty well theoretically, it still needs to be tested, modified, and improved via practical application. Chapter 4 studies the factors influencing prospective teachers’ beliefs about the three-dimension approach, as well as their intentions and practices related to it. Results showed that prospective teachers’ beliefs about the three-dimension approach seemed to be emerging and tentative. How to help prospective teachers change their negative attitudes towards the three-dimension approach and further develop their positive beliefs about it need to be studied. In addition, due to the constraints from contexts, some prospective teachers did not even get a chance to see how the three-dimension approach could be used in real science classrooms. In these cases, prospective teacher did they have the chance to try the approach in their practicum. How to facilitate prospective teachers’ learning of the three-dimension approach under the unfavorable conditions is a critical and urgent issue faced by science teacher educators.
References


http://arxiv.org/abs/1106.5801


Appendix A

Pre-survey

Try your best to answer the following questions without referring to other resources. We want to know your real beginning knowledge about engineering design. You will NOT be graded on your responses. If you have no clue about what to write, it is perfectly acceptable to write, “I do not know”, after any of the questions. Thanks!

1. List any engineering course you took before.

2. List your prior experiences with engineering design.

3. List your prior experiences with design other than engineering design.

4. Find or take some pictures which best represent your understanding of engineering design. Explain why you think they are typical examples.

5. Please name some important concepts involved in engineering design.

6. In your opinion, what important ideas included in engineering design?

7. If you were asked to do an engineering design activity, what practices do you think are involved in the design process?

8. In your opinion, what are the features of engineering design?

9. In your opinion, what are the similarities and differences between science inquiry and engineering design?

10. If you were asked to teach middle school students about engineering design, what do you think are essential content that needs to be taught?

11. Are there any other thoughts about engineering design, as well as its’ teaching and learning that you want to share?
Appendix B

Engineering Design Activity

Problems: An Alarm System in Hospital

A hospital needs an alarm system in the nurse office so that patients can call for help if they are in need. Specifically, when the patient in a particular room presses a button, the system will remind the nurses which room is calling for help. Your task is to help the hospital design an electric circuit system which can serve two separate patient rooms.

Materials: Batteries, buzzers, switches, wires, bulbs, battery holders, and bulb holders

Note:

1. You should build one circuit system rather than two separate circuits
2. Your circuits will be scored according to the grading rubric.

Material Cost:

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost for Each</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery</td>
<td>$5</td>
</tr>
<tr>
<td>Bulb</td>
<td>$10</td>
</tr>
<tr>
<td>Buzzer</td>
<td>$20</td>
</tr>
<tr>
<td>Wire</td>
<td>$2</td>
</tr>
<tr>
<td>Switch</td>
<td>$10</td>
</tr>
<tr>
<td>Battery holder</td>
<td>$5</td>
</tr>
<tr>
<td>Bulb holder</td>
<td>$5</td>
</tr>
</tbody>
</table>
# Appendix C

## Team Worksheet

<table>
<thead>
<tr>
<th>Team Members:</th>
<th>Team Report</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Circuits</td>
</tr>
<tr>
<td>First Try</td>
<td></td>
</tr>
<tr>
<td>Second Try</td>
<td></td>
</tr>
<tr>
<td>Third Try</td>
<td></td>
</tr>
</tbody>
</table>
1. List the circuit elements and calculate the cost of your FINAL design.

2. Analyze the advantages and disadvantages of your FINAL design.

3. What difficulties did you meet during your design process? Explain how you coped with the difficulties you meet.

4. Other thoughts you want to share.
Appendix D

Grading Rubric

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Levels &amp; Scores</th>
<th>Your score</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Finish design as fast as possible</td>
<td>Level 0: The last team that finishes the design (0 point)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Level 1: The middle three teams that finish the design (5 points)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Level 2: The first three teams that finish the design (10 points)</td>
<td></td>
</tr>
<tr>
<td>2. Your circuit should be able to achieve the desired functions.</td>
<td>Level 0: The circuits cannot achieve the desired functions at all. (0 point)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Level 1: The circuits can only remind nurse of the call from one patient room. The circuit can only alarm via light. (10 points)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Level 2: The circuits can only remind nurse of the call from one patient room. The circuit can alarm via sound. (20 points)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Level 3: The circuits can remind nurse of the call from both patient rooms. The circuit can only alarm via light. (30 points)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Level 4: The circuits can remind nurse of the call from both patient rooms. The circuit can alarm via sound. (40 points)</td>
<td></td>
</tr>
<tr>
<td>3. The total cost of the circuit should be as low as possible</td>
<td>Level 0: Total cost &gt; $100 (0 points)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Level 1: $85 &lt; Total cost ≤ $100 (5 points)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Level 2: $75 &lt; Total cost ≤ $85 (10 points)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Level 3: $65 &lt; Total cost ≤ $75 (20 points)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Level 4: $55 &lt; Total cost ≤ $65 (25 points)</td>
<td></td>
</tr>
<tr>
<td>Level 5: Total cost ≤ $55 (30 points)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Draw the circuit diagram of your final designs with symbols</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level 0: Five or more mistakes occurred in circuit diagrams (0 points)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level 1: Less than five mistakes occurred in circuit diagrams (10 points)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level 2: All circuit diagrams are correct (20 points)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Total score:**
Appendix E

Interview Protocol

We will ask you some questions about your experience and thoughts of learning and teaching engineering design. Your responses to these questions have **NOTHING** to do with your grades for the methods courses. Please tell us your **REAL** thoughts. Thank you for participating in this research!

1. Tell me about your circuits design experience.
2. What did you learn from doing the circuits design activity?
3. What did you learn from the presentations after circuits design activity?
4. In your future teaching, what will you do when your students meet difficulties during their design process?
5. From students’ perspectives, what do you need to consider when you plan engineering design lessons?
6. How will you use engineering design activity to promote your teaching in your future science classroom?
7. What kind of engineering design activity will you choose to support your science teaching?
8. How will you assess your students’ learning about engineering design in your future science teaching?
9. Is there anything else you want to share about engineering design, as well as its teaching and learning?
Appendix F

Sampling for Interview

<table>
<thead>
<tr>
<th>Participants</th>
<th>Levels of Initial knowledge of Engineering Design</th>
<th>Levels of Initial knowledge of Teaching Design</th>
<th>Number of participants</th>
<th>Sampling Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undergraduates</td>
<td>N</td>
<td>N</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>L</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>N</td>
<td>14</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>L</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Graduates</td>
<td>N</td>
<td>N</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>L</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>L</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>N</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
Appendix G

Pre-questionnaire

Write one or two sentences to the best of your ability in response to the following questions. Please do not use outside resources. We want to know your beginning knowledge. You will not be graded on your responses. We are only interested in what you know at this point, at the beginning of this course.

1. Write down one or two things you know about the new U. S. K-12 Science Education Framework and the Next Generation Science Standards [NGSS].

2. What are the science practices you need to teach to middle level students according to the new U. S. K-12 Science Education Framework and NGSS?

3. Name some crosscutting concepts in science that are appropriate to teach to middle level students according to the new U. S. K-12 Science Education Framework and NGSS.

4. Name some disciplinary core ideas in earth science, life science, or environmental science that are appropriate to teach to middle level students according to the new U. S. K-12 Science Education Framework and NGSS.

5. NGSS requires science teachers to integrate three dimensions (i.e. science practices, crosscutting concepts, and disciplinary core ideas) in classroom teaching. In your view, how might you integrate these three dimensions in your teaching practice? Give a teaching example to show your integration strategies.

6. What do you think about the three dimensions of the new U. S. K-12 Science Education Framework and NGSS?

7. What do you think about the three-dimension teaching approach proposed by the new U. S. K-12 Science Education Framework and NGSS?
Appendix H
Post-questionnaire

Write one or two sentences to the best of your ability in response to the following questions. Please do not use outside resources. You will not be graded on your responses. We are only interested in what you think at this point, at the end of this course.

1. How do you feel about the “integrating three dimensions” task proposed by the new K-12 Science Education Framework and NGSS at this time? Explain why.

2. What role do you think the “integrating three dimensions”, as proposed by the new K-12 Science Education Framework and NGSS could play in middle-school science TEACHING? Explain why.

3. What role do you think the “integrating three dimensions”, as proposed by the new K-12 Science Education Framework and NGSS could play in middle-school science LEARNING? Explain why.

4. Do you feel confident about using the three-dimension approach to teach middle school science? Explain why.

5. Have your feelings about the “integrating three dimensions” task changed during this semester? If yes, explain how.

6. If your feelings about the “integrating three dimensions” task changed during this semester, then what learning experiences contributed to your change?

7. Is there anything else you want to say about the three-dimension teaching approach proposed by the new K-12 Science Education Framework and NGSS?
Appendix I

Interview Protocol

Thank you so much for participating in our study! This interview will not have any influence on your grade of this methods course. We will use an audio-recorder to record the whole interview process. You can withdraw this interview whenever you want. We will use an alias to substitute your name in the future publication.

1. Tell me about your learning experience about the three-dimension approach in the methods course.

2. What subject did you teach in your practicum?

3. What science standards did your practicum school use?

4. Did you talk about the three-dimension teaching approach with your mentor teacher?
   What did she/he say about it?

5. How your mentor teachers’ comments on the three-dimension teaching approach influenced your thoughts about it?

6. Did you use the three-dimension approach to teach science in your practicum? Explain why.

7. Tell me about your teaching experience if you have taught science via the three-dimension approach in your practicum.

8. Is there anything else you want to share with us about your practicum experience?