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Integrating Nanotechnology into the Undergraduate Chemistry Curriculum: The Impact on Students' Affective Domain

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INTEGRATING NANOTECHNOLOGY INTO THE UNDERGRADUATE
CHEMISTRY CURRICULUM: THE IMPACT ON
STUDENTS' AFFECTIVE DOMAIN

by

Jacinta M. Mutambuki

A dissertation submitted to the Graduate College
in partial fulfillment of the requirements
for the degree of Doctor of Philosophy
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June 2014

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INTEGRATING NANOTECHNOLOGY INTO THE UNDERGRADUATE CHEMISTRY CURRICULUM: THE IMPACT ON STUDENTS' AFFECTIVE DOMAIN

Jacinta M. Mutambuki, Ph.D.

Western Michigan University, 2014

High attrition rates in science, technology, engineering, and mathematics (STEM) continue to be documented in the undergraduate education in the United States (U.S.). There is a growing concern that the U.S. will fall short of 3 million graduates by 2018. Furthermore, the literature indicates that about 36% of 4-year college graduates lack adequate critical thinking skills, complex reasoning, and communication skills relevant to the current job market. Reasons for these observations relate to the overemphasis on content knowledge; lack of content relevance; lack of interest in STEM courses; and dominance of expository teaching methods in classrooms. Given its relevance in society, nanotechnology can be incorporated into STEM curricula to increase content relevance, and students' attitudes towards the courses. This, in turn, can promote increased retention rates, as well as progression into STEM careers. However, little is known about the impact of integrated nanotechnology-science curricula on students' affective domain.

This project seeks to investigate the impact of two inquiry-based integrated nanotechnology-chemistry modules on students' perceptions and attitudes towards chemistry, and quantitative analysis chemistry laboratory course. In particular, the study investigates: (1) how undergraduate science majors perceive chemistry and the

quantitative analysis chemistry laboratory course; (2) how their perceptions and attitudes toward chemistry and quantitative analysis chemistry laboratory course change following exposure to the two nanotechnology-chemistry experiments; (3) the underlying factors for the observed perception and attitudinal changes; and (4) students' perceptions and attitude towards inquiry-based learning approach.

A mixed methods explanations-model design is employed. Data are collected through questionnaires, classroom observations, and interviews. Results indicate improvement of students' perceptions and attitude towards chemistry, and quantitative chemistry laboratory course. Major factors for the observed improvement include: relevance of nanotechnology concepts to students' daily-lives/society; novelty of the nanotechnology concepts; inquiry-based approach; integration of a wide array of chemical instrumentation in one lesson, and prolonged laboratory experience. Overall, nanotechnology is a conduit for increasing students' perceptions and attitudes towards chemistry, as well as promoting interest in the learning and progression into science-related careers. Furthermore, inquiry-based learning approach is well received by science major students, particularly those in advanced class levels.

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INTRODUCTION

This manuscript contains six chapters. Chapter 1 articulates the problem statement that guided the study herein. In discussing the problem, I highlight the current challenges associated with undergraduate science education, including chemistry programs. Under this chapter, I discuss (1) the purpose of the current study in addressing the identified key problems in undergraduate science education, particularly in the United States of America (U.S.A.); (2) the research questions based on the gaps identified in the literature; (3) the learning theory and theoretical framework guiding the study; and (4) the significance of the study in improving undergraduate chemistry curricula, and science in general.

Chapter 2 is a literature review, in which I discuss past research work surrounding the key concepts of the current study: chemistry laboratory work and instruction, content relevance with emphasis on context-based curricula, and nanotechnology education. I also discuss the context of the research, where I provide a description of the chemistry laboratory course in which the study was carried out and the nanotechnology related modules implemented in this course. In Chapter 3, I present a detailed methodology used in carrying out the study whereby I discuss the research design, data collection methods and procedures, and data analysis methods. Chapter 4 presents the results and Chapter 5 is a discussion of the results. Finally, Chapter 6 presents the conclusions drawn from the study, the implications of the findings in improving undergraduate science curricula in institutions of higher learning, and future research work that future researchers should strive to address in advancing the work discussed herein.

CHAPTER 1 : THE PROBLEM STATEMENT

Introduction

The quest for relevant science curriculum in the U.S. dates as early as the 18th century (DeBoer, 1991). According to the National Science Education Standards (NSES), content is fundamental if it: (i) represents a central event or phenomenon in the natural world, (ii) guides fruitful investigations, (iii) reflects situations and contexts common to everyday experiences, and (iv) can enhance meaningful learning experiences (National Research Council (NRC), 1996). Nearly two decades ago, the National Research Council (NRC) (1996) urged schools and colleges to embrace a relevant science curriculum geared towards preparing competent citizens. Despite this call, the literature indicates that many schools and colleges have continued to offer irrelevant science curricula with respect to the needs of students and society (e.g., Hofstein et al., 2011; Holbrook, 2005; Seymour & Hewitt, 1997). Consequently, high attrition of students in science, technology, engineering, and mathematics (STEM) programs has been documented in undergraduate education (e.g., Seymour, 1998; Seymour & Hewitt, 1997).

Seymour's and Hewitt's study of why students in STEM fields switch to non-STEM programs revealed that 83% of the participants indicated a lack of content relevance, poor teaching methods (90%), and lack of interest in science (60%) as the major reasons for switching majors. Moreover, a small group of senior STEM-majors (nearly 17%) on every campus studied were planning to switch for non-STEM careers following graduation (Seymour, 1998; Seymour & Hewitt, 1997).

Hitherto, the effects of attrition and under enrollment in the undergraduate programs are experienced in modern society. A recent report released by the Georgetown Center on Education and the Workforce indicates that by 2018, about 46.8 million job openings will be available in the United States (U.S.), with 33 percent (16 million) of the openings requiring a bachelor's degree or better (Carnevale, Smith, & Strohl, 2010). Jobs in STEM fields are among the top 5 occupations projected to attract a high number of workers by 2018. Unfortunately, colleges and universities continue to record high attrition of students, with the majority being underrepresented minorities and low-income students (Kelly & Lautzenheiser, 2013). Furthermore, half of the students who complete a bachelor's degree finish it within six years (U.S. Chamber of Commerce), and more than half (53.6%) of the bachelor's degree holders under the age of 25 years are either unemployed or underemployed (Press, 2012).

A study by Arum and Roska (2011) revealed that after four years of coursework in colleges, thirty six percent of the graduates did not show improvement in critical thinking skills, complex reasoning, and communication skills. There is a growing concern that the U.S. will fall short of 3 million graduates by 2018 (Carnevale et al., 2010). Besides financial constraints in affording education, another reason for this shortage may be due to overemphasis on the content knowledge, and use of teaching approaches that do not adequately prepare students with relevant skills for the job market (Holbrook, 2005).

Relevant science content that lead to student meaningful learning could be enhanced by incorporating "contexts" or situations that have real-world applications into the existing science curriculum (e.g., Bennett & Lubben, 2006; Gutwill-Wise, 2001; Pringle & Henderleiter, 1999; Schwartz, 2006). However, the literature indicates that

relevant chemistry curricula have been mainly targeted to high school students and non-science majors at the college level (e.g., Schwartz, 2006). There is a serious negligence of relevant chemistry curricula that reflect students' every-day life, particularly for science majors at the college level. For quality improvement of the undergraduate science education, redesigning of STEM courses to foster student interest and/or a positive attitude in the four-year education system is pivotal.

Another way to increase content relevance in undergraduate education is through integrating nanotechnology as a “context” into existing science curricula.

Nanotechnology is a field impacting various aspects of everyday life and several fields such as aerospace, agriculture, energy, the environment, healthcare, information technology, homeland security, national defense, and transportation systems (NNI, 2011). The unique size-dependent properties of nanoparticles make them super-ordinate and indispensable in society. Nanoparticles have potential applications in contemporary society such as biosensors in biology and medicine (e.g., detection of DNA, detection of pathogens, drug delivery for tumor destruction), sensors for water and environmental pollutants, among others (NNI, 2011).

Given its wide applications in modern society, nanotechnology has potential to positively impact students' attitudes towards science, which, in turn, can promote increased enrollment and retention rates in science programs, as well as ensure student progression into science careers, including women and underrepresented minorities. Additionally, incorporating nanotechnology into the existing science curriculum, including chemistry, will not only make the otherwise “abstract-taught” science concepts visible and relevant to students, but will also acquaint students with knowledge of

nanoscale science and nanotechnology and contribute towards the anticipated workforce in the nanotechnology industry.

While the advocates of nanotechnology education believe that nano-related concepts can provide authentic experiences for students through scientific inquiry, most of the reported modules implemented in the undergraduate curriculum follow the traditional method of teaching. The use of active teaching strategies such as inquiry-based approaches is likely to promote authentic experiences to students. Furthermore, laboratory environment is essential in providing students with authentic experiences, as well as promoting positive attitudes towards science (Shulman & Tamir, 1973). Although some attempts have been made to examine first year undergraduate chemistry students' attitude and perceptions about laboratory work (e.g., Miller, Nakhleh, Nash, & Meyer, 2004), little is known about advanced students' perceptions and attitudes towards chemistry and science in general. This project aims at addressing the aforementioned gaps. In particular, two inquiry-based integrated nanotechnology-chemistry modules have been developed and implemented in a 2000 level (sophomore) undergraduate chemistry laboratory course.

Statement of Purpose

The goal of this project is to increase student retention in science fields, as well as promote their progression into science-related careers, including chemistry, by cultivating positive attitudes towards learning. Ornstein (2006) asserts that “how well students perform in academic science courses, over the long run, is not as important as their understanding of broad science concepts and their attitudes toward science...these factors

will influence their reaction to issues that affect them and society” (p. 285). It is of great importance that educational systems recognize the pivotal role played by student attitudes and seek actions that will promote positive attitudes towards science (Ornstein, 2006).

Kerr (1964) posits that “throughout the school course we must be more aware of the need to maintain interest by learning through real problems or processes which, where possible, can be applied to real-life situations.... Further learning is more likely to take place if interest develops as knowledge increases” (p. 25). To prepare future citizens who can thrive and provide solutions to the global issues in contemporary society, it is imperative that students be exposed to relevant curricula. This project seeks to cultivate student interest and positive attitudes towards learning by exposing students to concepts that relate to their daily-experiences and/or real-world applications. Nanotechnology was integrated into the existing quantitative analysis laboratory course as a “context” to increase the relevance of chemistry concepts to students.

I conducted a follow up study to investigate the impact of two inquiry-based integrated nanotechnology-chemistry units on science major students’ perceptions and attitudes towards quantitative analysis chemistry laboratory course and field of chemistry in general. In particular, I was interested in investigating: (1) how undergraduate science majors perceive the experiments offered in the quantitative analysis chemistry laboratory course; (2) how their perceptions about, and attitudes toward the quantitative analysis chemistry laboratory course as well as chemistry and science in general, change as a result of the two inquiry-based integrated nanotechnology-chemistry experiments; (3) the factors, if any, which influence students’ change of perception, and attitudes toward the

quantitative analysis course and chemistry in general; and (4) the attitudes and perceptions of these students about the inquiry-based learning approach.

Research Questions

Based on the above mentioned objectives of the study, four main research questions guided this work:

1. How do undergraduate science majors perceive chemistry and science, and the quantitative analysis chemistry laboratory course?
2. How do the undergraduate science major students' perceptions about, and attitudes towards chemistry and science, and the quantitative analysis chemistry laboratory course, change, if at all, as a result of two inquiry-based integrated nanotechnology-chemistry experiments?
3. What factors, if any, influence the students' change of perception about, and attitudes toward chemistry and/or science and the quantitative analysis course?
4. What are the perceptions and attitudes of undergraduate science majors towards inquiry-based learning?

Learning Theory and Theoretical Framework of the Study

Constructivism learning theory. The current study is framed around the constructivism theory of learning (Bodner, 1986). This theory stipulates that knowledge is constructed in the mind of the learner in which prior experiences are vital in the reorganization of the mental structures to assimilate and accommodate information

(Bodner, 1986). Therefore, learning should be embraced as an active process in which students construct new ideas based on prior and/or current knowledge (Brandon & All, 2010). According to Jonassen (1991), a constructivist learning environment should: encompass the use of authentic problems or a feel of the real-world; represent the natural complexity of the real world; and support collaborative knowledge construction. Such environment calls for an active dialogue between the students and the instructor (Jonassen, 1991).

In a constructivist learning environment, the instructor's role is to encourage students to take control over their own learning while being mindful of their abilities and current state of knowledge (Brandon & All, 2010). Knowledge is, thus, not transmitted from the instructor to the learner (Bodner, 1986); rather students develop knowledge through an active knowledge construction process. Of great importance are the presentation of information and the nature of support offered to students in the knowledge construction process (Applefield, Huber, & Moallem, 2000). It is this knowledge construction process that distinguishes the constructivist classes from the traditional classroom setting (Brooks, 1990). While traditional classrooms are dominated by the transmission of information from the teacher to the students, constructivist model of teaching advocates that students should first explore the concepts through direct encounter with the materials with minimal guidance from the instructor before they are introduced to any given concepts (Brooks, 1990).

To produce competent workforce that can provide solutions to scientific issues in modern society, it is imperative that the constructivism learning approach be embedded in the undergraduate science education. In the current study, two modules were designed

and implemented in an undergraduate chemistry course in which the real-world applications of the nanotechnology concepts were integrated into the curriculum to make abstract concepts visible in the eyes of the students, as well as equip them with nanotechnology know-how needed in the future workforce. The modules were designed around the guided inquiry-based learning approach (Herron, 1971; Lederman, 1999), where students were provided with opportunities to design experimental procedures to investigate given problems. Detailed description of these modules is presented in Chapter 3.

Theoretical framework: affective domain. Affective domain is a theoretical framework that explains how human beings deal with things emotionally. It encompasses *feelings, values, appreciation, enthusiasm, motivation, and attitudes* (Krathwohl, Bloom, & Masia, 1964). In reference to the literature, attitudes can take two forms: “*scientific attitudes*” and “*attitudes towards science*”. “Scientific attitudes” apply to styles of thinking such as open-mindedness and objectivity (Garnett, Garnett, & Hackling, 1995; Hodson, 1990), critical-mindedness, skepticism, and willingness to consider the evidence (Garnett et al., 1995). According to Garnett et al. (1995), “attitude towards science” are emotions that include *interest, enjoyment, satisfaction, confidence* and *motivation*. The current study is centered on the latter component—*attitudes towards science*.

Significance of the Study

The research project described in this dissertation will provide insights about innovative approaches towards curriculum design and pedagogical strategies, through which students can connect with science field, engage in it, locate personal relevance, and

explore scientific or chemical principles from new and exciting dimensions. This paradigmatic shift, from content-driven to context-driven curriculum, may change students' perceptions and attitudes and draw them into the chemistry field, particularly women and underrepresented minorities. Most importantly, the study will provide insights to potential and specific factors that could be considered in the development of the curriculum to promote positive attitude or perceptions about chemistry field. This, in turn, may lead to retention in science majors and/or progression of these students into science-related careers.

Furthermore, integration of nanotechnology into the undergraduate chemistry curriculum will equip students with nanotechnology skills needed for the anticipated 1 trillion dollar nanotechnology industry by 2015 (Healy, 2009). The current study is a beginning step in preparing future nanotechnologists while making “abstract-taught” chemistry concepts relevant to students.

Findings on students' perceptions about the inquiry-based approach provide insights about the success of the inquiry-based approach at advanced chemistry levels. Positive perceptions are indicative that inquiry-based approaches need to be implemented not just for students in lower level, but also in advanced levels in the undergraduate science programs. Ultimately, this is vital in preparing potential future scientists, including chemists, with research skills needed in contemporary science or chemical industries.

Chapter Summary

In this chapter, I have highlighted the problem in which the current study is grounded. I have also discussed the purpose of the current study; the main research questions; the learning theory and theoretical framework surrounding the current study; and the significance of study in improving undergraduate science programs. In summary, I have emphasized the need for institutions of higher learning to embrace reforms in the undergraduate science programs to attract students into, retain them in science disciplines, and ensure progression in science related careers. Ultimately, this is important in addressing the shortage of current and future workforce in society. One approach to mitigate the challenge of workforce is offering relevant science curricula that promote student interest and attitudes towards science courses. My argument is that nanotechnology can be used as a tool to develop important technology, and when implemented into science curricula it can strength the relationship between real-world problems and fundamental scientific concepts.

CHAPTER 2 : LITERATURE REVIEW

Introduction

In this chapter, I present a comprehensive literature review of the state-of-art of laboratory work and instruction, content relevance, and nanotechnology education in science curriculum. More attention on these three areas has been placed on chemistry education in schools and higher institutions of learning. Furthermore, this literature centers mostly on the impact of the above mentioned areas on student learning outcomes, particularly on the affective domain. Prior to presenting the literature under each concept, I have articulated the conceptualization of the concept with respect to the scientific community.

Laboratory Work and Instruction

The terms “laboratory work” and “practical work” have been used interchangeably in the literature. According to Kerr (1963), practical work in science education refers to all kinds of experimental and observational activities, including laboratory exercises geared toward verifying scientific claims or measuring known outcomes. In their review published in 1982, Hofstein and Lunetta described laboratory activities as “contrived experiences in which students interact with materials to observe phenomena” (Hofstein & Lunetta, 1982). These authors add that the “contrived experiences may have different levels of structure specified by the teacher or laboratory handbook, and application as well as the central performance phase” (p. 202).

Hodson (1990) stated that practical work involves tasks in which students observe or manipulate real objects or materials for themselves or by witnessing teacher demonstrations. In the context of chemistry, Reid and Shah (2007) defined laboratory work as the activities that students undertake using chemicals and equipment (Reid & Shah, 2007). Hofstein's and Lunetta's (1982) definition of laboratory work, "*contrived experiences in which students interact with materials to observe phenomena,*" is adopted in this dissertation.

History of Laboratory Work and Instruction in American Schools and Colleges

Laboratory instruction has been known to be a distinctive area in science education since the 19th century. During this period, science had just taken shape from the European curriculum, in which academy schools took the lead in the implementation of science education in the American educational system (DeBoer, 1991). According to DeBoer, the quality of science teaching in the American academies in the 19th century was poor, and lacked utility and applicability. In particular, teachers were poorly prepared to teach various science courses; thus the courses were "book-taught, with the recitation of memorized texts the mode of instruction" (p. 20). Such science curriculum raised questions about its usefulness in the American society, even with the laboratory instruction. In 1945, Edward Hitchcock lamented about the science curriculum offered in the academies in which he succinctly asserted that:

With perhaps a few exceptions, our Academies do not possess the means of giving [an] elevated course of scientific instruction. The recitation of limited and imperfect text books, *with now then an experiment clumsily performed, and the exhibition of the*

battered, poorly characterized specimen, will by no means answer the purpose. And not much more than this can be done in most of our Academies for want of means. They do not possess, and cannot obtain, the requisite apparatus, nor afford to their instructors the time necessary to classify specimens and prepare experiments that shall be elegant, satisfactory, and full. (Cited by DeBoer, 1991, p. 20; italics added)

Although the shift in the American science curriculum in the academies and public schools emerged in the mid-19th C, reforms were evident in the late 19th C, that is, 1860s and 1870s, in which Pestalozzi's object lessons in science instruction was adopted in the American elementary schools. The shift referred to as "Oswego movement" initiated by Edward A. Sheldon, a Superintendent of Schools in the city of Oswego, New York, who came across Pestalozzi's curriculum materials displayed in a museum in Toronto, Canada, and taught in Pestalozzi based schools in Europe (DeBoer, 1991) build on the Pestalozzi's curriculum model—object lessons. According to DeBoer, Pestalozzi's curriculum model of science education emphasized the use of natural objects, which became accustomed in the American schools. Moreover, student engagement in the learning as opposed to "listening to memorized recitations of individual children who had prepared their work at home, or listened to the sing-song chorus of responses that children had learned through repeated drill" (p. 24) was highly emphasized.

According to DeBoer, the followers of Pestalozzi and Oswego movement made great impact on the American science education. For instance, Charles W. Eliot, president of Harvard University from 1869 to 1895 advocated for laboratory instruction at all levels of education in the American schools and emphasized science teaching as a mode of

empowering individuals to be independent and thrive in the society. In 1898, Eliot lamented the nature of science teaching in colleges in which he highlighted that college “students were receiving very limited training in scientific thinking” (DeBoer, 1991, p. 31). Laboratory instruction was thus deemed the right vehicle for enhancing scientific thinking in schools and colleges, and reforms advocated by Pestalozzi’s followers were implemented by the late 1890s.

Albeit its perceived significance in science education, laboratory instruction in the American schools and colleges conformed to verification of scientific claims or observation of natural phenomena as the main learning strategies. These flawed teaching strategies, in turn, were associated with high attrition rates in science courses in the early 20th century (DeBoer, 1991).

Consequently, “The project method” strategy invented by William Heard Kilpatrick in 1918 was believed to transform laboratory instruction to encompass more meaningful learning in which the science content was to become more practical and relevant to the student’s daily-life, that is, content organized around relevant social issues . Moreover, an inductive approach of teaching was deemed vital in laboratory classrooms. According to DeBoer, the inductive approach required students to make inquiries during the laboratory activities.

Overall, although other educators criticized the Kilpatrick’s proposal of “science for social relevance”, the shift from structured science content to social relevance content was evident in the American schools until the late 1950s, that is, the “progressive era—1917-1957” (DeBoer, 1991). In the subsequent section, I will discuss the purposes and/or

aims of the laboratory work or instruction in science education as stipulated by researchers and educators after the progressive era (i.e., from 1960s to 2012).

The Purpose/Aims of Laboratory Work

Johnstone and Al-Shuaili (2001) argues that the *purpose* of the laboratory differs from the *aim*. According to these authors, “*aim* refers to the scientific reason for a particular investigation, while the *purpose* is the way in which that investigation fits into the work being covered at that time” (p. 47). They further added that “awareness of aim is important as it helps learners make sense of what they are doing, while awareness of the purpose can encourage them to see the link between the activity and the rest of their science work” (p. 47).

A number of researchers have attempted to articulate the key purposes or aims of the laboratory/practical work. In his report entitled “Practical Work in School Science: An account of an inquiry into the nature and purpose of practical work in school science teaching in England and Wales”, Kerr (1963) presented a list of ten aims of the practical work in science:

- a) To encourage accurate observation and careful recording,
- b) To promote simple, common-sense, scientific methods of thought,
- c) To develop manipulative skills,
- d) To give training in problem-solving,
- e) To fit the requirements of practical examination regulations,
- f) To elucidate the theoretical work so as to aid comprehension,
- g) To verify facts and principles already taught,

- h) To be an integral part of the process of finding facts by investigation and arriving at principles,
- i) To arouse and maintain interest in the subject, and
- j) To make phenomena more real through actual experience (Kerr, 1963).

Shulman and Tamir (1973) proposed that science laboratory instruction should strive to:

- 1) Develop critical thinking and problem-solving skills;
- 2) Promote scientific thinking and scientific process;
- 3) Promote interest, attitude, motivation, satisfaction, curiosity and open-mindedness in science; and
- 4) Enhance the development of student conceptual understanding and practical abilities such as formulating procedures and designing experiments, collecting data using the formulated procedures, carrying out observations and collecting data, as well as analyzing and interpreting the data (Shulman & Tamir, 1973).

In addition to encouraging students to develop manipulative and observational skills, Buckley and Kempa (1971) stated that practical work should also promote students' ability to plan experiments and interpret experimental data. Refocusing on the laboratory work in introductory chemistry courses at university level, Venkatachalam and Rudolph (1974) argued that a freshmen chemistry laboratory course should aim towards acquainting students with:

- 1. Basic laboratory techniques and skills,
- 2. Knowledge and/or skill transfer from one laboratory context to another,
- 3. Synthesize relevant information to solve a given experimental problem,

4. Devise a procedure for data collection to address a given problem, and
5. Communicate adequately about the experimental results and their validity

(Venkatachalam & Rudolph, 1974).

In 1976, Anderson stated that the laboratory work should:

- a) Enhance student intellectual and aesthetic understanding;
- b) Promote the transfer of learned scientific knowledge and skills to real life applications;
- c) Allow students to appreciate and understand how scientists work by assuming their role; and
- d) Promote students' understanding about the principles of nature of science

(Anderson, 1976).

Moreover, Hodson (1990) argued that practical work can teach laboratory skills, enhance the learning of scientific knowledge, give insight into scientific method and develop expertise in using it, develop 'scientific attitudes', and stimulate the development of positive attitude towards science. Millar, Tiberghien, and Le Marechal (2002) asserted that lab work should help students make links between two domains of knowledge, namely: the domain of real objects and observable things, and the domain of ideas. Moreover, it should help students learn the scientific inquiry approaches (Millar, Tiberghien, & Le Marechal, 2002). In reference to the laboratory work in higher education, Buckley and Kempa (cited by Johnstone and Alshuaili, 2001) articulated the aims of laboratory work as promoting:

1. Manipulative skills;

2. Observational skills;
3. The ability to interpret experimental data; and
4. The ability to plan experiments.

Drawing attention to chemistry in higher education, Carnduff and Reid (2003) also articulated three main aims of laboratory work:

1. To enhance practical skills (including safety, hazards, risk assessment, procedures, instruments, observation of methods);
2. To promote transferable skills (including team working, time management, organization, data processing, designing strategies, problem-solving, etc.);
3. Intellectual stimulation by reflecting connections with the real world and raising enthusiasm for chemistry (cited by Reid & Shah, 2007, p. 176).

Others have stressed that laboratory work should teach hand skills, illustrate the theory (Hirvonen & Virii, 2002); help students develop concepts, processes, skills, facts, and attitudes (Abraham et al., 1997). Millar et al., argued that if the purpose of the laboratory work is not well thought out and planned, it can become purposeless to students (Millar et al., 2002).

To ascertain the value of the laboratory work in schools and universities, a few studies on teachers' and students' perceptions about the aims and the effectiveness of laboratory work in schools and universities have been documented in the literature (Abraham et al., 1997; Abrahams & Millar, 2008; Hanif, Sneddon, Al-Ahmadi, & Reid, 2009; Kerr, 1963; Venkatachalam & Rudolph, 1974). In the subsequent section, I will discuss past research work on students' and teachers' perceptions about lab work.

Teachers' and Students' Perceptions about the Laboratory Work

Kerr's (1963) work is among the first research work that document how laboratory work was perceived by teachers and students in the early 60s. In January 1961, he conducted a survey study with 701 science teachers (chemistry, $n = 218$; physics, $n = 258$; biology, $n = 225$) and 624 students (chemistry, $n = 136$; physics, $n = 305$; biology, $n = 183$) from 501 schools across England and Wales. The 701 teachers were sampled from the 1st to the 6th form levels of high school years. They were asked to rank the 10 aims of laboratory work summarized by Kerr (described earlier in this manuscript) in order of importance, that is, *1 = most important and 10 = least important*. Results on the ranking order by the teachers were follows: observation, elucidation, finding out, scientific thinking, manipulative skills, verification, reality, problem-solving, practical examinations, and interest (Kerr, 1963).

According to Kerr, while the findings indicated a general agreement on the emphasis of each aim across the three science disciplines among teachers, key differences on the pooled order of importance on the 10 aims were evident. For instance, observation, elucidation, finding-out, and scientific thinking were ranked the most important across the three courses. Furthermore, verification, finding-out, and problem-solving remained fairly the same across the school courses (1st to the 6th form level), while interest and reality became much less important as the school level advanced. In particular, interest was ranked as the most important aim of laboratory work at lower levels (year 1-2), but the least important at advanced level (6th form). Such ranking may have resulted from the view that at advanced level, the student should be already interested in the course; otherwise he/she would not have elected the course (Kerr, 1963). Similarly, reality was

ranked the 2nd important aim at the lower levels, but the 7th of importance at the 6th form level. Based on the poor ranking of interest and reality with advancing levels, Kerr posits two questions that need to be answered:

1. “Is the obligation to interest pupils taking advanced courses not acknowledged?
2. Does this partly account for the dull, unrealistic nature of much work in sixth forms”
(p. 30)?

Moreover, Kerr argued that maintaining interest is important at all stages of education, and thus should be highly regarded.

In February and March 1962, Kerr further carried out a survey with 624 form sixth students who continue their science education in Universities or Colleges of Advanced Technology. According to Kerr, the students were administered with 6 aims modified from the 10 aims administered to the teachers. They were asked to assign a number (1 to 4) opposite *each* of the six possible results of the practical work which they had *actually experienced* at school, to indicate the degree to which they thought they had been influenced (1 = greatly; 2 = moderately; 3 = slightly; 4 = not at all). The six aims were:

1. Helped me to observe more carefully.
2. Taught me to think more scientifically.
3. Made more clearly the theoretical part of the course.
4. Led to the finding out of facts and principles of which I was not previously aware.
5. Made the phenomena studied more real and interesting.

6. Gave training in manipulative skills.

Students' ranking results were as follows: interest and reality, elucidation (clarification), observation, manipulative skills, scientific skills, and finding out (Kerr, 1963).

A comparison of results based on the order of ranking as per the two groups (teachers and students) indicated controversial perceptions about the aims of laboratory work. While teachers viewed interest and reality as the least important aims of laboratory work for 6th forms, students in the universities and colleges felt these two aims were of great importance in their laboratory experiences. Kerr posited that future laboratory work should aim to promote interest and connections to reality at all levels of education. He said:

If pupils who go to the university are concerned that practical work in schools should be real and interesting, the other pupils, especially in the sixth forms, are even more likely to need this motivating influence... throughout the school course we must be more aware of the need to maintain interest by learning through real problems or processes which, where possible, can be applied to real-life situations. (p. 36)

Moreover, Kerr's findings indicated that one-fifth of the students in the sample felt that the "finding out of facts and principles" was "not important at all" and 66% of them were only "slightly" or less affected. Based on such findings, Kerr contended that schools are not making students conscious of the nature of the "finding-out" element in the science laboratory instruction. According to Kerr, students' ranking indicated that they were less influenced to think scientifically, even though the teachers throughout the school indicated their purpose was "to promote simple, common-sense, and scientific methods of thought" (p. 36). In

emphasizing the mismatch between what teachers stated they are trying to accomplish in laboratory instruction and what students say they achieve through the same, Kerr warned that:

If, through science teaching and especially through practical work, we are concerned with the development of a scientific way of thinking and behaving, then we must teach in such a way that our pupils are consciously aware of this goal. (p. 36)

Buying into the Kerr's (1964) claim about the matching of intended laboratory aims with appropriate teaching methods, Venkatachalam and Rudolph (1974) investigated the effectiveness of two teaching approaches in addressing specific general chemistry laboratory aims. They formulated five main objectives that students should acquire during their freshmen year of chemistry: (1) basic laboratory techniques and skills, (2) knowledge and/or skill transfer from one laboratory context to another, (3) synthesize relevant information to solve a given experimental problem, (4) devise an experimental procedure to address a given problem, and (5) communicate the experimental results and their validity.

Moreover, they implemented new teaching strategies, *learning cycle and challenge cycle*, to emphasize the aforementioned objectives, as well as promote creativity and scientific method in the learning. According to Venkatachalam and Rudolph (1974), the learning cycle precedes the challenge cycle, and involves (1) reading the assigned materials, (2) recitation- discussion session, (3) provision of cookbook/explicit directions about the experimental procedure and the expected results,

(4) discussion on calculations and laboratory write-up, and (5) obtaining feedback from the instructor.

Upon going through the learning cycle, students are exposed to the challenge cycle, where they (a) engage in open-ended questions phrased from a cookbook procedure, (b) design an experiment to investigate the problem, (c) collect data using their designed procedure, (d) carry out calculations and write-up, and (e) evaluate their results (Venkatachalam & Rudolph, 1974). According to these authors, while the learning cycle addresses objective 1 (i.e., the basic laboratory skills and techniques), the challenge cycle is believed to address objectives 2, 3, and 4 stated above. Their study involved 280 general chemistry students, divided into a control and a treatment group. The control group was exposed to the expository method of teaching, while the treatment group experienced the learning/challenge cycles.

Findings indicated that the experimental group gained more thorough understanding of the principles and logics behind their operations than the control group for five piloted experimental units (i.e., general laboratory techniques, chromatography, acid-base titrations, organic analysis, and spectrophotometry). Moreover, the experimental group indicated that the laboratory materials were clearly presented; laboratory experiments were more rewarding and interesting, and promoted creativity in the learning. However, the subsequent semester of exposure to the learning/challenge cycle model revealed that two convention experiments were deemed unrewarding and fostered no creativity to most students.

The post attitude survey indicated no statistical differences between the control and the treatment groups; both groups viewed chemistry as less favorable at the end of

the semester. Venkatachalam and Rudolph contended that learning/challenge-cycle is an effective laboratory teaching approach with considerable merit; students showed gains in conceptual understanding of the laboratory principles, as well as interest and appreciation in their learning.

Abraham et al. (1997) carried a similar study to Kerr's (1963) work in which they sought to examine the nature and the state of general chemistry laboratory courses offered by colleges and universities in the United States. The authors administered a survey instrument to general chemistry laboratory faculty from 203 randomly selected accredited colleges and universities. The faculty were asked to rank the following laboratory goals in the order of importance (*1 = most important to 5 = least important*): (1) concepts, (2) developing scientific processes, (3) developing laboratory skills, (4) learning factual information, and (5) developing positive attitudes towards chemistry, in the order of importance (Abraham et al., 1997).

Abraham et al. reported the following order of faculty ranking of the laboratory aims (from the most to the least important): *concepts, laboratory skills, scientific processes, positive attitudes, and learning facts*. In particular, the authors report the average scoring of the laboratory aims as follows: "*concept = 2.12, laboratory skills = 2.43; scientific process = 2.49; positive attitudes = 3.71; and learning facts = 4.31*" (p. 592).

Findings of the students' ranking of the five laboratory goals administered to the faculty showed a mismatch between the faculty priority laboratory goals and what students experienced in the laboratory environment. While the faculty felt that developing concepts is the most important goal in the laboratory, students expressed that laboratory

experience stressed factual knowledge and skills over concept development. Abraham et al.'s (1997) findings on faculty ranking of laboratory aims align well with teachers' ranking in Kerr's (1963) study. It is surprising that faculty regard students' positive attitudes as among the least goals laboratory work should strive to achieve at college, or university level.

Refocusing on the role of laboratory experience, some researchers and educators continue to express their grievance about the ineffectiveness of laboratory work in promoting meaningful learning in high schools and higher institutions of learning. Reid and Shah (2007) claim that experts tend to present content in accordance to what they value rather than giving priority to students' needs; thus, there is little evidence that laboratory work enhances the achievement of the stipulated laboratory aims (Reid & Shah, 2007). Reid and Shah pinpoint the root of this problem to be the overemphasis on the experiments to be performed and little emphasis on what students should gain from the laboratory experience.

In answering to the call on the evaluation of effectiveness of the laboratory work, Abrahams and Millar (2008) conducted a case study with 11-year-old to 16-year-old students in maintained schools in England. These authors' study was guided by the research question: "how effective is practical work in school science, as it is actually carried out, as a teaching and learning strategy" (p. 1946)? The authors adapted the laboratory effectiveness model suggested by Millar et al. (2002) as their framework of the study. The laboratory effectiveness model includes three elements:

1. Teacher's objectives— this encompasses what the teacher wants the students to learn. It may comprise of scientific knowledge or specific aspects of the process

of scientific inquiry such as data collection, analysis, or interpretation of empirical evidence,

2. Design of practical work task—is envisioned to enable students to achieve the desired learning objectives, and
3. What students actually do as they undertake the task.

Abrahams' and Millar's (2008) study involved a multi-site approach comprising of 25 case sites in eight schools. Data collection methods comprised of classroom observation field-notes on practical work augmented by interviews (pre-lesson and post-lesson interviews with teachers) conducted in the context of the observed practices. The observations were done in eight comprehensive secondary schools offering science lessons at national curriculum for Key Stage 3 (11-14 years-old) or Key stage 4 (15-16 years-old).

According to these authors, the practical lessons observed were purposely selected to allow for: pre-lesson and post-lesson interviews, even coverage of the five school years in Key Stages 3 and 4 (i.e., 11-12, 12-13, 13-14, 14-15, and 15-16 years-old), as well as lesson observations with different teachers while ensuring the inclusion of biology, chemistry, and physics topics. The number of observed lessons based on the three science subjects included: Key Stage 3 (11-14 years): Biology = 2; chemistry = 6; Physics = 7, and Key Stage 4 (15-16 years): Biology = 1; Chemistry = 3; Physics = 6. The total number of lessons observed in Key Stage 3 was 15, while those observed in Key Stage 4 were 10 — a total of 25 cases (Abrahams & Millar, 2008).

Their findings indicated that, often times, the practical work observed was effective in helping most of the students to achieve the teacher's intended objectives with

the objects—generating the intended phenomena. The authors claim that success in achieving the teacher’s intended outcome was enhanced by the use of ‘cook-book’ style tasks. This approach was prevalent because of insufficient time to have students design and set up apparatus within a 1-hour practical lesson, generate the intended phenomenon as well as record, analyze and interpret the data. Also, teachers put high priority in having students produce the intended outcomes.

Teachers ensured that students understood the procedure they had to follow for successful execution of the task; however, there was little evidence that the tasks were effective in promoting students’ thinking about the same objects and materials using either implicit or explicit ideas intended by the teacher (Abrahams & Millar, 2008). According to Abrahams and Millar, the teacher’s approach of the lesson dictated the extent to which students made successful links between the domains of observables and ideas. They noted that opportunities provided to students to think about the observables using scientific ideas were scarce, and some teachers presented detailed procedural instructions to the students— which they confirmed to be their intended approach to getting students successfully generate and record the intended data. The authors contend that based on the 25 observed lessons, “the practical tasks used were ineffective in helping students to see the task from a scientific perspective and to use theoretical ideas as guide to interpreting their observations” (p. 1960). Teachers valued the experimental outcomes over the underlying scientific ideas.

The authors also reported that students showed ability to recall and report accurately on the things they had done with the objects and materials involved, and the phenomena they had observed based on the evidence of short-term learning within the

lesson or post-lesson student interviews, as well as students' comments based on similar practical work they had previously done. Student post-lesson interviews revealed that many students were able to recollect information about what they had done or seen the teacher demonstrate, with objects and materials. However, such recollection of information yielded less to recalling a particular task done or specific aspect of the task. The recollection of information was attributed to tasks that exhibited the following characteristics:

1. A distinctive sensory such as aural, visual or olfactory component— 27 of the 68 tasks recollected mostly related to these components;
2. Novel context or manner or presentation—18 tasks comprised of tasks presented in an unusual context or manner (e.g., tasks carried out in different locations rather than in the normal laboratory); and
3. A 'gore' factor— evident in three of the recollected biology tasks (Abrahams & Millar, 2008).

Additionally, the authors report that the recollection of procedures by students related to what they had done rather than the ideas it was intended to convey— the understanding of the concepts in question.

Moreover, there was little evidence of students' learning of the ideas from the activity, that is, conceptual understanding of ideas based on the post-lesson student interviews (Abrahams & Millar, 2008). According to these authors, students showed little evidence in recalling the observables, ideas, and/or making links between these domains, even when guided towards making such links. None of the students was able to illustrate recollection of scientific ideas involved in the recollected tasks. This might be due to the

fact that most teachers emphasized on getting the activity done to generate the intended phenomena, rather than promoting student understanding of the concepts behind each task (Abrahams & Millar, 2008).

Overall, the authors highlighted a gap between the teachers' thinking and planning, and the emphasis of the key scientific knowledge and scientific inquiry underlying each task. That teachers' emphasis on the teaching of the practical work focused more on science content rather than on the experimental design or the collection, analysis, and interpretation of evidence. The authors also reported a significance difference between the domain of observables and the domain of ideas. They discredit the teachers' claims that students learn theoretical ideas as a result of carrying out tasks with objects and materials, yet such was not visible in the observed lessons— very little time was devoted to promoting the development of ideas.

The authors challenge the teachers' use of an incompetent approach that appeared to be “inductive” in nature, but that assumed the teacher's intended ideas would emerge from the observation irrespective of how guided the observations were. They argue that to enhance a successful link between the domains of observables and ideas, and improve the effectiveness of the practical activity, ideas should be introduced during the practical activity rather than after, to account for the observed phenomenon. They propose that through scaffolding, students can be helped to scientifically see the phenomena in question in the same manner the teacher does. They also argue that teachers should spend more time in the lesson helping students to use the relevant ideas to make sense of the observed phenomena, rather than dwelling on the product of the practical activity— the phenomenon itself.

Summary

Kerr's (1963) findings based on the teachers and students' responses seem to align well with Abraham et al.'s (1997). In both studies, the instructors felt that developing positive student attitude towards science courses, including chemistry, is not very important. On the other hand, students felt that the main aim of laboratory work should be to foster their interest towards learning the subject-matter. This raises a lot of concern because if such is not considered a key element in the laboratory instruction, particularly by the instructor, how then do we expect students to continue as chemistry majors? In the light of the Kerr's and Abraham et al.'s studies, there is a need to re-think the laboratory science curricula offered in schools and colleges, and their effective in helping students to develop positive attitudes towards learning, as well as progression into the science programs, including chemistry. According to Kerr (1963), "further learning is more likely to take place if interest develops as knowledge increases. Interest is an avenue to science learning; it is a means of motivating the pupil to learn" (p. 25).

Abrahams and Millar (2008) provided light into why the instructors' views about the aims of laboratory work may be at odds with students' views. One key factor they highlight is the mismatch of the teachers' intended objectives of the laboratory work with their teaching approach. From their classroom observations on the science lessons taught by their teacher participants, Abraham and Millar noted that the teachers focused more on the science content rather than scientific thinking and/or the process of science (i.e., experimental design or the collection, analysis, and interpretation of evidence), even though such were stated as the intended objectives of the lessons in the teachers' scheme of work. The authors also reported that very little time was devoted to promoting the

development of ideas. Furthermore, the study conducted by Venkatachalam and Rudolph (1974), although may seem outdated indicate that using inductive teaching methods in which students are provided with the opportunity to own the learning are likely to enhance the achievement of specific laboratory aims.

In the subsequent sections, I discuss the literature pertaining chemistry instruction in colleges and universities. I draw attention to the literature on the impact of chemistry laboratory experiences on students' perceptions and attitudes towards chemistry, as well as the impact of inquiry-based instruction on student learning at the college level.

Literature on Laboratory Instruction in Colleges

Following the call by educators and researchers to change the mode of instruction in undergraduate science education, inductive instructional strategies suggested in the 19th C became visible in the schools and the universities in the late 20th C. In his review of laboratory instruction styles, Domin (1999) presents a summary of the instructional styles implemented in the chemistry laboratory instruction, namely: expository, inquiry, discovery, and problem-based instruction. A description of each instructional style is presented below.

Expository Instructional Style

This style is also known as traditional or verification style, and is most commonly used style in many science laboratories. Expository style follows a deductive approach from a given procedure, and the outcome is predetermined or known to both the instructor and the students. The instructor provides the task/topic to be investigated,

explains step-by-step procedure to the students, clarifies the expected outcome (predetermined outcome), and finally students repeat the given procedure by the instructor or from the manual or “cookbook” procedure to obtain the predetermined outcome(s) or to verify claims. This style is limited in that it does not promote students’ scientific thinking (formulating questions, designing experiments, collecting data and making interpretation, etc.), conceptual change, and emphasizes only lower-order cognitive skills (Domin, 1999).

Inquiry-Based Instructional Style

According to Domin, this style follows an inductive approach in which students are given an opportunity to generate their own procedure to investigate a problem whose outcome is not known to both the instructor and the students. Fewer directions are given for inquiry-based activities and are known to promote student engagement and ownership in the learning. Unlike the traditional/expository style, inquiry-based instruction exposes students to higher-order cognitive skills such as hypothesizing, predicting, explaining, inventing, evaluating arguments, interpreting, inferring, judging evidences, et cetera (Domin, 1999) which enhances scientific inquiry. According to Domin, inquiry-based learning activities do not only provide students with the opportunity to “engage in a process of learning the same concepts and principles that the scientist learned as a student, but also learning the processes and methods of science” (p. 544). There are two most common types of inquiry instruction—open-ended inquiry and guided inquiry.

Open-ended inquiry instruction. Involves students taking responsibility for their own learning in which they generate the research problem or questions, devise their own

procedures to investigate the problem, collect and analyze or interpret data, as well as generate claims and explanations to answer their research problem based on the empirical evidence derived from their observations (NRC, 1996). In this approach, the teacher's role is to guide students without telling them what to do in generating answers to their questions. Therefore, students dominate the whole learning process with extremely minimal guidance from the teacher (Lederman, 1999).

Guided-inquiry instruction. This approach involves presenting students with a research problem or questions, and allowing them to devise their own methods to collect data in an effort to find solutions to the research questions/problem. Like the open-ended inquiry, students apply their analytical skills to support their conclusions on the investigated research question (s) /problem based on the empirical evidence of their collected data. Overall, teacher involvement in guiding students through this approach is greater than with the open-ended inquiry. The teacher should formulate the research questions that students need to answer. I contend that while discovery instruction may encompass elements of inquiry-based instruction, it is not guided-inquiry per se; rather it is one of the facets of active learning strategies (Herron, 1971).

Discovery and Problem-Based Instructional Styles

Domin describes discovery instruction is an inductive approach in which the outcome is predetermined (known only by the teacher), and students are given the procedure to conduct the experiment, whereas problem-based instruction style is a deductive approach in which the outcome is predetermined by both the instructor and students, with students given opportunity to formulate the procedure for collecting key

data to test student-generated hypotheses. However, classification on the latter approach seems to be at odds with Prince's and Felder's (2007) classification. While Domin categorizes this approach as deductive, Prince and Felder (2007) considers it as an inductive approach, even though both Domin's and Prince's and Felder's description of problem-based learning match perfectly. According to Domin, the problem (relevant to real-world) must be identified first, and should guide the entire investigation and learning. Often times, the problem(s) is open in nature, and students navigate through their own paths in an attempt to answer their generated questions as well as test their hypotheses. In problem-based environment, students are required to "think about what they are doing and why they are doing it" (p. 546).

According to Prince and Felder, a team of students is presented with ill-structured open-ended real-world problem to solve in which they are particularly required to define the problem. They proceed by figuring out the known facts and the facts to be determined, then formulate and evaluate alternative solutions from which they select the best and make a case for it, and evaluate the lessons learned from the task (Prince & Felder, 2007). Prince and Felder add that "when they [students] identify the need for instruction on new material, the instructor provides it or guides the students to obtain the required information themselves" (p. 15).

Problem-based instruction is known to promote higher-order cognitive skills by allowing students to generate their own questions and hypotheses, formulate a procedure for investigating the problem, and answer and/or test their hypotheses following their observations on the investigation (Domin, 1999). Moreover, Prince and Felder (2007) cite a number of studies in which problem-based learning (PBL) has been associated with

long-term knowledge retention, ability to apply learned material, improved skill development, improved problem solving skills, development of teamwork skills, among others. However, this approach is the most difficult to implement, as it is time consuming to construct good ill-structured open-ended problems to address the intended learning objectives.

Overall, although inquiry, discovery, and problem-based instruction styles are associated with meaningful learning, they are more time consuming and demanding on both the students and instructor (Domin, 1999), and are more likely to provoke student resentment and resistance (Prince & Felder, 2007) than expository or traditional methods. To better establish the effectiveness of each instructional style in chemistry laboratory instruction, Domin argues that:

Researchers must go beyond comparing the general learning outcome, student achievement. Research is needed that addresses which style of instruction best promotes the following specific outcomes: conceptual understanding, retention of content knowledge, scientific reasoning skills, higher-order cognition, laboratory manipulative skills, *better attitude towards science*, [and] a better understanding of the nature of science. (p. 547; italics added)

While the aforementioned four instructional styles (Domin, 1999) are evident in chemistry laboratory teaching, Lagowski (2002) argues that “a clear direction for laboratory instruction based on research is not yet available to teaching chemists” (p. 1). Lagowski’s claim may have some validity in that non-significant difference between the traditional and constructivism strategies of teaching have been documented in a number of studies conducted in the 20th century (Hofstein & Lunetta, 1982). Following such

research findings, it is not surprising that direct transmission of information and “cookbook” procedures continued to be embraced, even in the 20th century albeit the existence of constructivism approaches. A study conducted by Hilosky, Sutman, and Schmuckler (1998) confirms this claim.

Hilosky et al. (1998) compared the status of laboratory-based instruction in chemistry at the beginning college level in the U.S.A and Germany. Their study involved 24 general chemistry instructors and 3000 students from 16 diverse institutions of higher education (IHEs) located in the Northeast region of the U.S.A, and one general chemistry instructor from one IHE in Germany. According to these authors, the instructional approach from both countries differs for general chemistry courses. The 16 IHEs in the U.S.A included private and public two-year and four-year colleges and large universities. The authors collected data through direct observations and videotaping of instruction during 24 pre-lab, post-lab, and actual chemistry laboratory sessions. Their findings from the laboratory sessions in the U.S.A indicated that “supervising students’ laboratory work” occupied most of the time spent in laboratory instruction. Moreover, the authors mention that instructors spent little time asking students to explain their observations using chemical theory, or listening to students’ explanations. Additionally, there were no assessments on student learning that developed directly from the laboratory experiences.

Furthermore, 23 of the 24 observed laboratory sessions in the U.S.A revealed that instructors gave direct answers to the students’ questions regarding procedural questions. Only in one laboratory session that students were encouraged to refer to the written directions. According to the authors, there was little opportunity for students to develop habits that would sustain self-motivated learning. On the other hand, classroom

observations on the general chemistry laboratory in Germany indicated that instead of being provided with cookbook procedures, students were provided an opportunity to look for relevant procedures from other sources, or worked in groups to design the expected procedure for the activities with minimal guidance from the instructor. In addition, students looked for resources that would help them draw explanations on the observed phenomena (Hilosky, Sutman, & Schmuckler, 1998).

Findings on the laboratory guides used in the U.S.A indicated that students are directed to the following steps:

Read the directions for carrying out the experiments and answer a set of preliminary questions; follow and carry out the stated procedures; make observations and record the results related to these observations in the tear-out forms; and answer specific questions based on the recorded data. (p. 102)

In contrast, students at the same level in Germany are expected to: clearly record the procedures in a laboratory notebook; carry out the recorded procedures; reason out and interpret the collected data; draw conclusions based on the collected data; and hand in the completed laboratory report to the instructor for feedback. In German, student assessment of the laboratory work constitutes final oral examinations focused on the understanding of concepts from the laboratory experience, and is conducted by the instructor and the head of the department. During the final examination, each student is asked to explain the observed phenomena using chemical theory in which they are given opportunity to refer to their laboratory notebooks. According to the authors, laboratory experiences in German offered students with the opportunity to develop higher-order thought processes,

as well as own the learning—self-motivated learning (Hilosky et al., 1998). A summary of the authors’ findings on laboratory instruction in both countries is presented in Table 2.1.

Table 2.1 A Comparison of Laboratory Instruction in the U.S. and German IHEs

16 U.S. IHEs	A German IHE
Instructor is often present in the laboratory	Instructor is seldom present in the laboratory
Instructor directed and controlled the activities	Students planned for, and directed the activities
Students often depended on the instructor on procedural matter	Students are independent of instructor on procedural matter
Students interact with instructor concerning procedures to be followed	Students often interact with instructor in discussion of theory
Logic and thinking are not individually addressed by instructor	Logic and thinking are individually addressed by instructor
Use of analytical instrumentation and computer technology	No use of analytical instrumentation and computer technology

Based on their findings, Hilosky et al. recommended the following changes in the beginning college level laboratory courses which can also be extended to the advanced chemistry courses:

- a) Reducing the number of the investigations within a given course, as well as proving more flexibility in the use of materials by students.
- b) Training or retraining laboratory instructors to serve as guides in the learning where they can provide students with opportunities to plan and direct their own learning, and
- c) Redesigning assessment procedures to reflect major laboratory objects.

The subsequent section is a discussion of research work on students' perceptions about, and attitudes towards chemistry instruction at the college level.

Instructional Approaches and Students' Perceptions and Attitudes at College Level

Developing positive attitudes towards science has been stated as one of the crucial aims of laboratory work. According to Ornstein (2006), developing positive students' attitudes towards science is equally important as their understanding of scientific concepts, and more important than their academic performance in preparing them as competent citizens who can make rational decisions in society. He said:

How well students perform in academic science courses, over the long run, is not as important as their understanding of broad science concepts and their attitudes toward science. As adults, these factors will influence their reaction to issues that affect them and society as well as whether they support or oppose proposed political decisions. It is therefore imperative that educational systems recognize the important role played by student attitudes and seek actions that will achieve a positive view. (p. 285)

In an attempt to understand the ways in which students' attitudes toward science could be enhanced, Shibley and Zimmaro (2002) conducted a study with 100 first year chemistry students enrolled for an introductory chemistry course at Penn State University in the United States. These authors looked at the impact of collaborative learning on student attitudes and performance in the course. Forty four students participated as the control, while fifty six students participated in the treatment group. Students in both groups were exposed to the same experiments, except that the treatment group (collaborative) was provided with supplementary materials highlighting modifications on

the experiments, for example, running two experiments in parallel (i.e., two set ups for one experiment) and comparing the results. The treatment group also performed their experiments in groups of four but each student was required to submit an individual report. Groups in the treatment sections selected their leaders and the role had to be equitably rotated among the group members during the semester.

Shibley's and Zimmaro's (2002) findings showed that students in the treatment group felt that they: (1) learned more when working in groups, (2) were able to better learn the lecture material, (3) were more comfortable asking questions in class, and (4) showed interest in enrolling for another chemistry course. Forty one percent (41%) of students in the treatment group also indicated that collaborative group learning helped in conceptual understanding and 20 % indicated that group work made the laboratory more enjoyable, interesting, and fun (Shibley & Zimmaro, 2002).

Miller, Nakhleh, Nash, and Meyer (2004) sought to understand the attitudes and conceptual understanding of first year chemistry students towards chemical instrumentation in the quantitative analysis course, in a research-based university in the U.S.. Their assessment of students' attitudes and understanding in the course focused on 4 main instrumental techniques: *infrared (IR) spectroscopy, flash/column chromatography, thin-layer chromatography (TLC), and gas chromatography (GC)*. Their study is framed around the "*distributed cognition*", an extended form of constructivism in which "individuals construct knowledge through a complex set of interactions with other people and with artifacts in their environment" (p. 1801). Their study was guided by three main research questions:

1. What are students' attitudes toward using chemical instrumentation in the laboratory setting?
2. How do students relate the chemistry concepts to the instrumentation?
3. How does teamwork affect students' attitudes toward, and their conceptual understanding of the chemical instrumentation?

Miller et al. employed field observations, structured surveys, and interviews as means of data collection in a second-semester general chemistry course intended for chemistry majors. The course covered topics such as thermodynamics, equilibrium, kinetics, electrochemistry, transition-metal chemistry, and nuclear chemistry. The course was a 5-credit with three lectures, one lab, and one recitation. Students were divided into groups of three to four individuals for the lab and recitation meetings. Forty four ($n = 44$) students participated in the study.

According to the authors, fundamental principles of the four chemical instruments were covered in the lecture prior to the laboratory experiments that required the use of such instruments. Moreover, students completed an IR assignment using IR tutor package during the first two weeks of the semester. The field observations was done on one group of students ($n = 12$) during the recitation and in the lab while working with three different chemical instruments and two different lab techniques to complete a single experiment, that is, separating and identifying compounds in a mixture.

The survey items were constructed at the end of the experiment, and were based on the observations noted as students conducted the experiment. The survey consisted of 4 demographic questions (gender, major, year of school, and lab section), as well as 25

Likert-scaled items (1 = strongly disagree and 5 = strongly agree), and 6 free-response questions. The structured items were categorized into 5 areas: (i) comfort operating chemical instruments, (ii) conceptual understanding (iii) effects of errors, mistakes, and modified procedures, (iv) group dynamics, and (v) general questions. The 6 free-response questions asked students to identify the easiest or the most difficult instrument to use as well as understand conceptually, as well as to identify the least or most enjoyable experience during the experiment. According to the authors, only 14 of the 44 students (32%) completed the survey.

Six volunteer participants (4 males and 2 females) participated in the interviews, which were conducted as follows: individual interviews with one male and one female student, a focus group of two males, and a focus group of one male and one female. During the interview, the participants were given a copy of the experiment and asked to share their thoughts about the goal of the experiment, as well as the professor's intentions in choosing the experiment. Trends gathered from the survey and classroom observation, as well as students' attitudes towards the experiment were further probed during the interviews. In addition, students were interviewed about their conceptual understanding of the chemical instruments (Miller, Nakhleh, Nash, & Meyer, 2004).

The authors identified five major themes from the three data sources: *Simplicity, clear explanations, group work, valuable skills, and conceptual understanding*. Findings on simplicity indicated that students identified TLC as the most "simple", yet "complicated" instrument to use. According to Miller et al., an instrument was regarded as "simple" if it was easy to operate, and "complicated" if students had to run multiple trials instead of one. Moreover, all the participants valued a clear explanation of the

concepts underlying the instruments prior to handling the instruments during the lab session. In addition, the authors' findings revealed that students experienced difficulties in visualizing flash column chromatography. One explanation the authors provided for the perceived difficulties was the lack of a demonstration of the operating principles of the instrument—the students were only presented with a white and black diagram.

Findings on group work revealed that students valued working in groups as they could help each other understand the experiment and save time. The valuable skills learned from the experiment consisted of deductive skills, critical thinking skills, and analytical skills, especially from the conflicting data that they generated. Some students felt that they developed management skills, particularly in organizing people to function co-operatively (Miller et al., 2004).

Findings on students' conceptual understanding indicated that students developed a better understanding of the underlying concepts (i.e., chemical instrumentation) following detailed information about such instrumentation presented to them during lectures, labs, or in computer modules. In particular, students had a better understanding of IR (Mean = 3.71) and GC (Mean = 3.79) from the lecture section as well as the IR assignment they completed early in the semester. However, the interviews revealed that they did not think of the underlying concepts until the preparation of the lab report. *According to Miller et al., most students were concerned about data collection and leaving the lab, rather than understanding the concepts underlying the experiment* (Miller et al., 2004).

Overall, students experienced different conceptual changes following the experiments. For instance, one student questioned the simplicity of IR prior to the

experiment, but appreciated it as the simplest analytical technique after the experiment. The authors also pointed out that the interviewed female had no prior knowledge on any of the techniques prior to the experiment; however, she understood how the instruments functioned and the reasons for using such instruments during the experiments. In contrast, the Focus Group 1 comprising of the two males indicated that although they developed critical thinking skills as a result of the experiment, their conceptual understanding was not affected by the experiment. For instance, they felt that their conceptual understanding on chromatography did not change as a result of the experiment—“*chromatography all works the same*” (Miller et al., 2004).

In conclusion, Miller et al. highlighted that students developed positive attitudes toward using instrumentation in the laboratory. Their participants indicated that they developed a better conceptual understanding of flash chromatography, IR, and GC instruments because they were well explained in the lecture and during the lab. Furthermore, most students felt that they developed a better conceptual understanding of the instruments they used in the lab during the preparation of the laboratory report. In addition, students appreciated working in groups.

Based on their findings, they advised that (1) detailed theory on the purpose and the functioning of chemical instrumentation or techniques should be thoroughly discussed in a lecture section prior to the lab and/or during the pre-lab lectures, (2) experimental design should encompass capabilities of the instrument or technique, and (3) experimental design should encompass questions that probe students to predict and interpret data during and/or after the experiment (Miller et al., 2004).

Oliver-Hoyo and Allen (2005) conducted a study with 167 general chemistry students in which they compared the attitudinal effects of a student-centered environment with a teacher-centered setting. The teacher-centered setting (control group) involved a typical lecture section of 119 students while the student-centered environment (treatment group) –what the authors refer to as “Student-Centered Activities for Large Enrollment Undergraduate Programs (SCALE-UP)”, involved 48 students. According to Oliver-Hoyo and Allen, SCALE-UP involves incorporating hands-on activities, cooperative group learning, real-world applications, and technology into the learning environment. The control group attended 3 hours of lecture per week, 3 hours of lab every other week, and 1 hour recitation sessions that were offered on alternating weeks. One instructor taught both sections in which a transmission model was employed in the lecture section (control) — students were passive learners. On the other hand, the treatment group attended three sessions per week of an integrated lecture and lab format with each session lasting for 2 hours. The instructor facilitated the learning and familiarized students with technology—students were active participants in the learning (Oliver-Hoyo & Allen, 2005).

According to these authors, both groups were administered with pre- and post-surveys during the first and the last two weeks of classes. The survey items included 14 questions to gauge students’ attitudes toward learning science and 25 questions to monitor chemistry anxiety in learning, evaluation, and chemical handling. Additionally, students (n = 161) completed a departmental evaluation with items tailored to the course as well as the instructor. Oliver-Hoyo’s and Allen’s (2005) findings on the evaluation survey indicated no significant difference on the students’ perceptions about the

instructor between the two groups, although students in the treatment group gave lower instructor ratings than the control group based on the surveys.

Findings on chemistry anxiety showed a significant decrease in anxiety for chemical handling for both groups. However, based on the pre-post-surveys a significant increase in anxiety for learning chemistry was more evident for students in the control group than in the treatment group, that is, the treatment group showed an increase in anxiety for learning chemistry in 4 of the 10 questions, while the control group showed increased anxiety for learning chemistry in all of the 10 questions. Finally, findings on student attitudes toward learning science indicated positive changes in which 77.1% of the students in the treatment group (SCALE-UP) showed positive residualized gain scores based on the pre-and post-surveys. The authors argued that student responses to the open-ended questions from the department survey indicated “numerous, positive, and more inspiring” feedback for the SCALE-UP section than the traditional lecture section.

Berg (2005) examined the factors related to observed attitude change toward learning chemistry among university students. He was interested in understanding the factors related to students’ shift in attitude toward learning in a university chemistry context, and the relative significance of these factors. His study is framed by the Perry’s theory of intellectual and ethical development of college students which portrays a developmental process in individual’s personality traits. According to Berg, Perry’s model exhibits the following positions or categories: (1) *dualism* (Perry position 1-2) — right or wrong view of the world, in which the learner can learn the truth from the authorities; (2) *multiplicity* (Perry position 3-4) — represents dualism (right or wrong) with the addition of “not yet known”. The role of the learner is to find knowledge and

reason individually; (3) *contextual relativism* (Perry position 5-6) — looking at things as context-bound, with few right and wrong answers; rather than the view that there are many exceptions to right or wrong. The learner is actively engaged in making meaning within a context; and (4) *commitment within relativism* (Perry position 7-9) — concerns elaboration of identity rather than cognitive change. Only a few undergraduate students reach this position (Berg, 2005).

Berg utilized Perry's positions in which he analyzed students' attitudes towards learning by looking at the views of knowledge, assessment, laboratory activities, and perceptions of the roles of instructor and student. According to Berg, sixty-six out of the 72 students enrolled in a full time introductory chemistry course in a university in Sweden completed a pre-and post-attitude survey instrument. Forty-three of the 66 participants were females and 23 were males. The participants were from different majors such as chemistry, biology, chemical engineering, biological engineering, and teacher training. The chemistry course investigated covered general, inorganic, organic, physical and biochemistry concepts, and comprised of the whole-group lectures, tutorials, seminars, and laboratory activities in which students were grouped into 12-15 individuals, except for the lectures.

An attitude survey instrument consisting of 34 items based on Perry's work and others was administered on the second day and the 20th week of the chemistry course. Of the 66 students who completed the attitude survey instrument, six were selected for in-depth open-ended interviews. The selection followed students who exhibited large attitude change towards learning. According to Berg, the interviews sought to understand the factors that led to the displayed change in attitude based on the pre-and post-attitude

survey responses. The interviews were conducted 4-6 weeks after the end of the course which lasted for 1-2 hours. The interviewees were asked to (1) provide their demographic information on their previous education, working experiences, future plans, etc., (2) describe their experiences on the introductory chemistry course they were enrolled in, and (3) provide additional thoughts about parts 1 and 2 above.

Three of the selected six students displayed high positive attitude shifts and three displayed a greater negative attitude shift. Berg utilized the *principal component analysis* (PCA) method to determine the variability of the participants' responses on the survey items. According to Berg, PCA is a "multivariate technique in which several related variables are transformed into a smaller set of uncorrelated variables, principal components.... It explains variability and has a unique solution..." (p. 4). The instrument was tested on 1000 students for over four years for reliability and validity purposes.

Berg's findings indicated all the interviewees displayed motivated behavior. However, students with positive shifts showed higher frequencies in the categories of motivated behavior such as *choice, level of activity and involvement, and persistence*. Although students with positive shifts expressed some negative statements regarding the level of activity and involvement (2 negative statements) and persistence (5 negative statements), there were no negative statements on the choice category for such students. According to Berg, most interviewees made several positive choices in studying chemistry prior entering the university. Some students with positive shifts had enrolled for more chemistry courses than required in their undergraduate programs, unlike those with negative shifts.

Regarding the instructional activities, students with negative attitude shift made negative choices in their learning. Furthermore, findings on the level of activity and involvement showed that all students with positive attitude shift studied 40 hours per week or more, including lectures and classes, whereas one student with a negative shift indicated such. Also, students with a positive shift demonstrated more conscious and aware of their study strategies, particularly staying in phase with lectures. In contrast, two of the students with a negative shift expressed a decline in their involvement in the course over time.

Findings on persistence behavior and regulation of effort in learning indicated that the three students lacked persistence with new tasks and course demands— one student expressed that planning for laboratory activities was time consuming. According to Berg, although these students seemed to understand the relevance of the tasks, they were not persistent with tasks that were ill-structured or ill-formulated (i.e., demanding tasks) like their counterparts with positive shifts. Moreover, students with positive shift were persistent with learning demands and remained focused, even after failing exams.

Findings on contextual factors (nature of tasks, reward and goal structures, instructional methods, and instructional behavior), indicated that the three students with positive attitude shift appreciated tutorials that were broader and had open-ended questions— they believed that such tutorials were useful in helping them in processing deeper knowledge. Furthermore, an appreciation of demanding tasks such as planning laboratory activities that are open-ended in nature was evident among the students with positive shift. Berg also noted that students with positive shift did not value the connections or applications of chemistry to biology— one student stated that she

appreciated tasks without connections to biology, while students with a negative shift valued chemistry tasks that had biological connection.

Five of the six students (3 students with positive shifts; 2 with negative shifts in attitude) interviewed highlighted that good examination results promoted self-confidence in the learning (reward and goal structures). Moreover, asking questions and obtaining answers was appreciated by the three students with positive attitude shift and one student with a negative shift. According to Berg, all the six students described “good teachers” as providing students with the opportunity to ask questions, giving alternative explanations to clarify concepts, providing clear goals and structured problems, and being aware of difficulty concepts in chemistry that students need extra help on. Descriptions of “bad teachers” comprised of: “seeming to become angry when students ask questions; answering by saying “*this is the way it is*”, and seeming to “*want to be somewhere else*” (p. 11).

Berg presented educational implications that universities could implement in promoting student attitude towards chemistry. Among these implications are:

1. Providing opportunities for collaborative group learning,
2. Relating/connecting chemistry to other subjects,
3. Providing clear directions for ill-structured tasks or new tasks (e.g., the need for students to plan experiments), and
4. Creating an atmosphere where students can ask questions, as well as being aware that students may not grasp everything immediately.

Ozden's (2008) study involved 627 first and second year university who attended an introduction to general chemistry course. He looked at the gender differences in student attitudes towards chemistry, as well as the correlation between attitudes toward chemistry and students' academic major. His study addressed the research questions: (1) "Are there gender differences in student attitudes toward chemistry? (2) Is there a correlation between attitudes toward chemistry and student's academic major?" (p. 92). He also hypothesized that (1) no gender difference between male and female students' attitudes toward chemistry, and (2) no correlation between students' attitudes toward chemistry and their academic major (Özden, 2008).

Ozden designed a survey instrument comprising of 20 Likert-scale type items that focused on attitude towards learning chemistry. The instrument was administered to students in the faculty of education, and who were enrolled in a chemistry introductory course. The 20 survey items were categorized as positive and negative statements (Özden, 2008).

Findings indicated a significant difference between the male and the female students' attitudes toward chemistry in which male showed more positive attitudes than females ($F = 28.5$; $p < 0.01$). For instance, he mentioned that while 58% of females indicated they strongly agreed or agreed with the statement —"All chemicals are harmful", only 39% of the males agreed with the same item. Fifty six percent (56%) of the females did not believe that "chemistry can provide solutions to many of the world's problems" while 52% of the males agreed with this statement. Ozden also pointed out that 58% of the females indicated that "chemistry is a difficult subject", while 41% of the males agreed with this statement. Ozden explains that the noted differences in gender

attitudes may be due to the Turkish cultural socialization, as females are offered less exposure to scientific and technological events and instruments than males. Also, a majority of the females (59%) agreed with the statement: “Chemistry makes me restless, irritable and impatient”, while only 43% of the males agreed with this statement. Ozden argues that this feeling may be influenced by the sensitive and emotional structure of females compared to males in the society.

Findings on academic areas and attitudinal scores showed significant difference between every academic area and the students’ attitudes towards chemistry ($F = 9.27$; $p < 0.01$). The Scheffe’s test results gave the reported F ratio values below:

1. Elementary school teacher training and Mathematics teacher training, $F = 21, 44$;
2. Elementary school teacher training and Science teacher training, $F = 24, 85$;
and
3. Science teacher training and Mathematics teacher training, $F = 32, 96$.

Students in the Science teacher training and Mathematics teacher training programs showed more positive attitudes towards chemistry than their counterparts in other academic areas. Students in Elementary school teacher training and mathematics teacher training programs showed the most negative attitude towards chemistry.

Based on his findings, Ozden contended that: “the content of instruction programs and the textbooks need to change to improve female students’ attitudes toward chemistry in a positive way” (p. 95). He urged future researchers to investigate the attitudes of experienced teachers toward chemistry. He also suggested that differences in students’

attitudes toward their non-major courses should be considered in developing lessons and new curriculum, as well as choosing pedagogical strategies. Furthermore, he emphasized that instructional designers should consider involving credible and attractive women role models to address the emotions that are associated with existing attitudes. He also urged researchers to examine the following areas:

1. Strategies for improving all students' attitudes toward chemistry, especially female students;
2. Why and when attitudes toward chemistry begin to change; and
3. Factors affecting attitudes toward chemistry, especially gender differences.

Summary

In this section, I have discussed the comprehensive literature related to students' perceptions and attitudes toward chemistry. Attention has been drawn to studies that have focused on student attitudes and perceptions at the college level. The studies reviewed in this section reveal fundamental findings about student attitudes towards chemistry at an introductory level, and provide directions for future improvement of student positive attitudes towards chemistry.

Miller et al.'s (2004) study indicated that students developed positive attitudes toward the use of instrumentation in the laboratory, and appreciated working in groups. The authors stressed the need to ensure students develop conceptual understanding about the operating principles of the instrument prior to using it in the lab. One of the suggestions posited by the authors is the use of probes during laboratory instruction to

elicit student reasoning during the experimental design, prediction of data, and interpretation of data during and after the experiment.

Berg's (2005) study indicated that students with positive shifts showed higher frequencies in all three categories of motivated behavior: choice, level of activity and involvement, and persistence compared to students with negative attitudes towards chemistry. Such students also appreciated tutorials that were broader and had open-ended questions for they believed that such tutorials were useful in helping them process deeper knowledge. Furthermore, an appreciation of demanding tasks such as planning laboratory activities that are open-ended in nature was evident among the students with positive shift. These students were also persistent with learning demands and remained focused, even after failing exams. Students considered good instruction as the one that provides them with the opportunity to ask questions, provides alternative explanations to clarify concepts, provide clear goals and structured problems, and addresses the difficult concepts and areas that students need help on.

For future improvement of undergraduate curriculum, Berg (2005) urged universities to consider: (1) providing opportunities for collaborative group learning, (2) relating/connecting chemistry to other subjects, (3) providing clear directions for ill structured tasks or new tasks— e.g., planning experiments or tutorial questions with no clear, single answer, and (4) creating an atmosphere where students can ask questions while being aware that they may not grasp everything immediately.

Ozden's (2008) study revealed a gap in gender and attitudes towards chemistry in which a majority of the female students showed negative attitude towards chemistry than male students. He suggested that differences in students' attitudes toward their non-major

courses should be considered in developing lessons and new curriculum, and pedagogical strategies. He also recommended that future work should seek to understand: (1) the strategies for improving all students' attitudes toward chemistry, especially female students; (2) why and when attitudes toward chemistry begin to change; and (3) factors affecting attitudes toward chemistry, especially gender differences.

Inquiry-Based Instruction in Undergraduate Chemistry Laboratories

Inquiry-based approach has been perceived as a “central strategy to science teaching” (NRC, 1996, p. 31). According to the NRC, Inquiry learning is an active learning strategy in which, “students describe objects and events, ask questions, construct explanations, test those explanations against current scientific knowledge, and communicate their ideas to others. They identify their assumptions, use critical and logical thinking, and consider alternative explanations” (p. 2). The learning activities involved in this approach include:

Making observations; posing questions; examining books and other sources of information to see what is already known; planning investigations; reviewing what is already known in light of experimental evidence; using tools to gather, analyze, and interpret data; proposing answers, explanations, and predictions; and communicating the results. (NRC, p. 23)

Following the NRC's call for schools and colleges to implement student-centered approaches such as inquiry in the U.S., many K-12 schools have heeded to the call as evidenced by the number of publications. However, many colleges and universities

appear to trail in implementing the same— very few studies have been documented in the literature, with most of them focusing on general chemistry laboratory instruction. It is indubitable that many colleges and universities continue to use expository instruction as the common strategy despite the criticism made by several educators about this strategy. Based on the many aims of laboratory instruction previously discussed, expository method rarely helps students in achieving most of the aims. According to Johnstone and Al-Shuaili, although the expository method can provide students with manipulative and data collection skills, it may not provide students with the opportunity to plan experiments, it is unrealistic in presenting scientific experimentation, and may offer little motivation towards learning (Johnstone & Al-Shuaili, 2001).

Past research indicate that students subjected to student-centered approaches such as inquiry learning show learning gains in terms of performance scores, increased student engagement in the learning process (Abraham, 2011; Schwartz-Bloom & Halpin, 2003), improved conceptual understanding (Gormally, Brickman, Hallar, & Armstrong, 2011), problem solving (Schwartz-Bloom & Halpin, 2003), development of students' laboratory investigative skills (Suits, 2004), improved communication skills, feeling of ownership and responsibility in the learning, development of a learning community (Tsapalis & Gorezi, 2005), and improved student confidence and positive attitudes towards the processes of scientific inquiry (Lucas & Rowley, 2011).

Despite the aforementioned benefits of inquiry-based approach, colleges and universities lag behind in implementing this approach in the undergraduate chemistry programs (Abraham, 2011). According to Abraham, although a majority of 203 general chemistry instructors who participated in a survey study (discussed earlier herein) on

laboratory goals indicated that ‘learning concepts’ is the most important laboratory goal, his study revealed that most instructors do not use inquiry-based approach; rather they employ the expository method of teaching (Abraham, 2011). While one explanation may be that the faculty are not familiar with the inquiry approach, it is also likely that they think students will learn concepts more easily with cook-book labs. A scrutiny of the literature shows that there are very few inquiry-based experiments published in chemistry journals (e.g., Journal of chemical education), as well as few follow-up studies on the impact of inquiry-based approach on student outcomes at the college level (Lucas & Rowley, 2011; Suits, 2004; Tsaparlis & Gorezi, 2005).

Suits (2004) examined the impact of inquiry-based approach on students’ development of scientific investigative skills at the college level. The study was conducted at a mid-sized state university in the South of the U.S.. Participants involved students enrolled in the introductory-level chemistry courses — science and engineering majors (SEM) and non-SEM students. The non-SEM composed of students from nursing and applied science fields. The motivation to conduct the study followed an innovation of an inquiry-based instructional approach and a change on the prerequisites for the introductory chemistry curriculum in the university in question.

According to Suits, the initial curriculum required students to complete two semesters of general chemistry. The course was four-credits each semester and comprised of a lecture class (80% of grade) and the laboratory session (20% of grade). The new curriculum comprised of two semesters of the lecture course – each 3-credits, three-credit lecture course coupled with a co-requisite 2-credit laboratory course, and a 1-hour post laboratory discussion.

One hundred and fifty two (152) students participated in the study. The students were grouped into a control and two treatment groups. The control group comprised of science and engineering majors (SEM-Ctrl; $n = 59$ students), while the treatment groups consisted of nonSEM majors (nonSEM-Trt; $n = 42$ students) as well as students from SEM majors (SEM-Trt; $n = 51$ students). Three research questions guided the author's study:

1. "What is the effect of [a] laboratory instructional method upon the acquisition of six scientific investigative skills (quantitative measure)?"
2. How does [a] laboratory instructional method affect the number of students who acquire a coherent set of investigative skills at the "midrange competent" and the fully competent" levels (quantitative measure)?"
3. What are student perceptions of their thinking skills used during a practical examination (qualitative method)?" (p. 3)

The control group (SEM-Ctrl) was taught in the fall semester through the traditional method—verification approach, what the author calls Level II. Emphasis was put on the hands-on activities with little attention paid to the pre-laboratory preparation (a pre-lab quiz and a pre-lecture). Students met once per week for 3-hour laboratory period. The treatment groups were taught in the spring semester, and were exposed to an inquiry-based approach in addition to three stages of laboratory investigation (Level III): pre-laboratory preparation, experimental work, and post-laboratory analysis.

At the end of the course, students from the three groups were presented with a laboratory challenge experiment for a laboratory practical examination. The challenge

experiment was to assess students' performances in formulating their own procedure and investigating the chemical phenomena (Level IV). According to Suits, the three groups participated in three stages of scientific methodology. The first stage (pre-laboratory stage) lasted for 30 min and involved providing students with a problem statement and having them to develop and write their own procedure, as well as a list of materials/equipment required by gathering both known and unknown facts from the problem statement. Students were given an opportunity to refer to their laboratory lecture notes and previously graded laboratory reports. They then turned in the write up to the teaching assistants (TAs) after which they were allowed a 10 min break – in which they were encouraged to discuss their procedures and predictions (Suits, 2004).

The second stage lasted for 2 hours and involved hands-on activities. All the relevant materials/equipment were available in the laboratory room. According to the author, SEM students completed their laboratory activity and gathered their own data while the nonSEM students worked in pairs. During the third stage, students wrote their laboratory reports and turned in for grading. A rubric scaled from 0 to 3 (i.e., 0, 1, 2, 3) was used to assess student performance on the laboratory work, with zero (0) awarded if none of the investigative skills stated above was evident, and 3 awarded if an investigative skill was explicitly written, and /or accurate.

The findings on the first research question (i.e., investigative skills component) based on the pairwise t-test comparison between the SEM-Trt and SEM Ctrl indicated that the treatment group (SEM-Trt) scored significantly higher ($p < 0.05$) than the control group (SEM-Ctrl). Students from the treatment group were better able to plan and describe a procedure for the experiment, collect data based on their observations, and

compute the necessary calculations from their data than their counterparts in the control group. The findings further revealed that the treatment group wrote better and longer discussions ($M = 6.02$ lines, $SD = 2.68$) than the control group ($M = 3.17$ lines, $SD = 2.72$) in comparing the observed results with the expected results, as well as verifying, in the light of the evidence, if the experimental objective had been achieved. Suits states that the statistical differences between the two groups might have been due to differences in ability, interest, or background of the students (Suits, 2004).

The pairwise t-test comparison between the SEM-Trt (science and engineering majors) and NonSEM-Trt (nursing and applied science majors) showed that the SEM-Trt group performed significantly higher ($p < 0.05$) than the NonSEM-Trt group on all the investigative skills, except on the procedural steps. According to Suits, there were no statistical differences between the groups for the exceptional investigative skill. T-test results on the performance of the SEM-Ctrl and NonSEM-Trt groups indicated that NonSEM-Trt group was better able to discuss the accomplishment of the objectives ($p < 0.002$) than the SEM-Ctrl group. Furthermore, the NonSEM-Trt group wrote a significantly longer discussion ($p < 0.001$; $M = 7.36$ lines, $SD = 2.55$) compared to the SEM-Ctrl group ($M = 3.17$ lines, $SD = 2.72$). However, students in the control group (SEM-Ctrl) obtained slightly better results ($p < 0.07$) than did the NonSEM-Trt students. Suits highlighted that such differences might have been due to the length of exposure on the hands-on activities between the two groups—the SEM-Ctrl had twice as many hours of hands-on activities (i.e., 3 hours weekly for a period of two semesters) in comparison to the NonSEM-Trt group (3 hours weekly for a period of one semester).

Findings on the “development of laboratory competence” indicated that a majority (75.5%) of the SEM-Trt and a few students (30.5%) from the SEM-Ctrl group developed a midrange competence (i.e., 2 points on five of six investigative skills). The author concluded that the inquiry-approach implemented for the treatment group (SEM-Trt) was effective in developing a logical set of laboratory investigative skills than the traditional approach implemented for the SEM-Ctrl group. Further analysis also revealed that 28.6% of the NonSEM-Trt attained this level. A comparison among the three groups also indicated that there was no statistical difference between the two SEM groups for the fully competence level, that is, 3 points on the five of six investigative skills—only 4 (6.8%) SEM-Ctrl students and 5 (9.8%) SEM-Trt students met this criterion. However, none of the students from NonSEM-Trt group attained this level. Suits argues that such differences may be attributed to NonSEM students’ lack of interest in science, mathematics aptitude, and inadequate chemistry knowledge required in attaining a full laboratory competence level.

Findings on the qualitative data indicated that students were able to critically think rather than memorize and recite answers. Suits pointed out that the SEM-Trt students were aware of the demand on thinking skills required by the type of challenge they were to solve. However, students expressed challenges in “devising, executing, and explaining in writing a procedure for conducting a scientific investigation” (p. 9).

Suits contended that a laboratory practical examination can serve as a tool for measuring the value or impact of laboratory instruction in helping chemistry students develop scientific investigative skills. He claimed that the required competence level of an instructional approach should match the students’ capabilities, and that cookbook

/verification-type of experiments in most undergraduate chemistry laboratories should be transformed to incorporate investigative processes (Suits, 2004).

Tsaparlis and Gorezi (2005) investigated the impact of inquiry/project-based experiments incorporated into a conventional physical chemistry laboratory on chemistry students. Among the issues addressed by these authors included the experiences of implementing the laboratories, and students' experiences in carrying out the experiments. The study was conducted with third year, fifth semester, undergraduate chemistry students at the University of Ionnina, Greece, in the fall 2003. The physical chemistry laboratory course was the second and the last practical course in physical chemistry. According to the authors, the typical conventional physical chemistry laboratory course consisted of eight conventional experiments—four on electrochemistry and four on chemical kinetics. Also, students conducted one experiment per week — each lasting for 4 hours, and worked in pairs.

The modification of the conventional laboratory course involved the incorporation of an inquiry/project-based component where the students, in groups of four, were assigned a project to work on for the entire semester. Eight projects were assigned to the students in which only one group consisted of three students. All the projects were taken from the *Journal of Chemical Education*, and involved experimental procedures except one project that was theoretical in nature (i.e., Born-Haber cycle). According to the authors, the latter was used for comparative purposes in the study. Students were provided with additional instructional materials from the instructor or from the conventional laboratory manual. The eight project topics included:

1. Solvent-ion interactions in salt water;

2. Graphical presentation of the Born-Haber cycle for estimating the electrode potentials of metals (*Theoretical in nature*);
3. An undergraduate physical chemistry experiment on surfactants: electrochemical study of a commercial soap;
4. The solubility product of PbCl_2 from electrochemical measurements;
5. Electrochemistry of the zinc-silver oxide system;
6. Lithium batteries: A practical application of chemical principles;
7. The hydrogen electrode; and
8. A demonstration of corrosion by different aeration.

According to the authors, each group had to work on the assigned experiment each week and report the progress during the subsequent laboratory sessions. The first session of the course dealt with the conventional experiments, while the last session of the course was devoted in carrying out the inquiry/project-based experiments. A week prior to the latter session, the students worked closely with the instructor, the laboratory technician, and other members of the chemistry department to gather the required materials and equipment. At the end of the semester, each group was required to prepare a written report and do a 30-minute public oral presentation in a form of a special seminar. The seminar comprised of three sessions: oral presentations, a coffee break, and a lunch break. It began at 9 am and ended at 4.15 pm. According to the authors, the oral presentations on the projects were scheduled to allow for an alternation between the more theoretical and the more practical projects. Also, each session concluded with a project that was considered more interesting.

Data were collected through observations and questionnaires. The observations were employed during the hands-on activities, as well as on the oral presentations.

Findings showed that students were dedicated, patient, and enthusiastic about their projects. They attributed this to the originality of the projects and ability to take ownership and responsibility in the learning. Findings on the oral presentations and written reports showed that while the reports were excellently written, the oral presentations were poorly organized and students mostly read from their reports. Students' general opinions on the project work indicated that most of them liked collaborative group learning. One third of the students indicated that the group members did not contribute equally (Tsaparlis & Gorezi, 2005).

Moreover, fourteen students expressed that they were happy with the projects, while 13 were neutral in their responses. Among the reasons on positive responses were: good cooperation (8); understanding of theoretical aspects (7); sufficient bibliography (7); interesting subject (6); and getting experience in public presentations (5). The reasons for negative responses included: the subject not interesting (1); unsatisfactory presentation (1); insufficient time to carry out the project (2); difficult cooperation (1); lack of experimental data (1); and work overload (1). Additionally students expressed the major challenges in carrying out the project as: foreign (English) literature (Mean = 1.8); laboratory facilities (Mean = 1.7); presenting the project in public (Mean = 1.4); application of the laboratory techniques (Mean = 1.3), among others (Tsaparlis & Gorezi, 2005).

The findings also indicated that students felt that working in groups should be part of their education (Mean = 3.4). Among the major reasons for incorporating collaborative group learning were: creating a sense of community of learners (15); exchanging ideas and reaching a consensus (8); and gaining varied learning processes.

A comparison between the project work and the conventional expository laboratory data on development of different student abilities indicated major improvement in: (a) communication skills characterized by familiarization with foreign (English) literature, search for literature, presenting the work to the peers (public presentation), scientific writing, collaborative group work, taking ownership in learning, connection of theory with modern scientific reality; and (b) skills related to psychology of learning such as the motive for learning, personal self-image, and critical thinking. The authors contend that incorporating inquiry/project-based projects in a conventional physical chemistry laboratory course can overcome the serious problems associated with “cook-book” traditional laboratory courses.

Lucas’s and Rowley’s (2011) study sought to examine the experiences of first year chemistry students in using Enquiry-Based Learning (EBL) approach to teaching spectroscopy. The study was conducted in the U.K. They examined how student perceived confidence change, if at all, as a result of their experience in using EBL, in the spectroscopy course, as well as students’ attitudes towards the processes of EBL and how these change through the course.

The main study involved 84 students, who had some prior knowledge on spectroscopy from their A Level program in chemistry. During the introduction to the EBL spectroscopy classes, the students were administered with a questionnaire geared toward examining their understanding of how the four aforementioned spectroscopic techniques operates, as well as their perceived confidence in their ability to interpret spectra from such techniques. The same questionnaire was administered at the end of the EBL course. Students were divided into 14 groups of six, based on their rated abilities in

interpreting the spectra. At least one student with perceived confidence in one of the four spectroscopy techniques was placed in each group. However, the groups' composition was based on the students' perceived ability, and not their actual ability in interpreting such spectra (Lucas & Rowley, 2011).

The spectroscopy course comprised of five sessions, each accompanied by a different task and ordered based on the degree of difficulty (from simple to complex). During the first session, students established group rules and each group was given same spectra of two simple compounds to interpret. The second session comprised of a discussion of the interpretation of the spectra from the first session- facilitated by a staff member with questioning at each stage, followed by an introduction to "waste disposal" scenario. According to the authors, each group received a memo stating that "*the unknown chemical waste was found in some disused laboratories and their help was required to identify the unknown compounds so that they could be disposed of safely*" (p. 480). The memo was accompanied by spectra (IR, mass, ^1H and ^{13}C NMR) of 8 compounds. Each group was given 8 more compounds to identify, and were required to hand in their reports and peer-assessment forms at the beginning of the third session.

The third session involved debriefing and giving written feedback to the students on their reports. This was followed by a "Down to Drain" scenario (also used in the pilot study), in which the groups received a memo stating that "dead fish had been found in a nearby river due to unknown chemical waste" and each group was required to identify compounds in the chemical waste like in the waste disposal scenario. Each group received a set of 8 spectra different from each other, and was required to hand in their reports and peer-assessment forms at the start of the fourth session.

The fourth session involved debriefing the students on what they should have identified in the task, followed by an introduction to “Carbonyl Conundrum” scenario, where each group was given 24 randomly-ordered spectra, and asked to match the spectra to the appropriate molecule. Each group was provided with four spectra for the 6 molecules, with the key peaks highlighted. All the groups were required to turn in their reports at the end of the session (Lucas & Rowley, 2011). The fifth session ran for two weeks, and entailed a “Reaction Dilemma” scenario, in which students were given spectra obtained from within the school, with the key peaks not highlighted. Students were required to interpret the spectra, explain the mistake in the reaction, and submit an individual report and peer-assessment of their group activities.

According to the authors, 42 students completed the questionnaire on student confidence and 32 students responded on the attitude questionnaire. Their findings on the student perceived confidence indicate an overall increase in student confidence in their ability to interpret spectra following EBL intervention (i.e., based on the pre-and post-questionnaire responses). However, a minority of the students displayed a decrease in confidence. The findings on the students’ self-assessed confidence in understanding how the techniques work indicated that students perceived good understanding of the Mass and IR spectroscopy techniques before and after EBL with 36% and 45% displayed increase, respectively, in student perceived confidence after the intervention of EBL. They noted that students lacked confidence in understanding how ^{13}C NMR functions prior to EBL sessions. However, 83% of the students indicated a perceived gain in confidence after the EBL sessions.

The authors also reported that students were confident in interpreting ^1H NMR, mass, and IR spectroscopy prior to and after the EBL sessions. The perceived increase in confidence in these three techniques was 41%, 38%, and 44%, respectively. They also identified that students lacked confidence in interpreting ^{13}C NMR spectra. However, a tremendous increase (76%) in student confidence in the ability to interpret ^{13}C NMR spectra was noted upon completing the EBL sessions. Furthermore, students valued working in groups as well as problem solving individually within the group, and having direct communication via cellphones with other group members over the online discussion board in WebCT. They expressed that EBL helped them think on their own. However, they indicated that the “scenarios” were somewhat redundant. The authors concluded that EBL has the potential to increase students’ perceived confidence in spectroscopy, especially for students who are less confident in spectra interpretation.

Summary

The above discussed studies reveal that inquiry-based approach enhances the development of investigative skills in a laboratory environment (Suits, 2004); improves students’ communication skills and skills related to psychology of learning such as the motive for learning, personal self-image, and critical thinking (Tsapalis & Gorezi, 2005); and can increase student confidence in interpreting spectra (Lucas & Rowley, 2011). Nonetheless, there is insufficient information about the impact of inquiry-based hands-on experiments that reflect a normal classroom setting on student outcomes. Although students in Suits’ (2004) treatment group were exposed to inquiry-based experiments

during the course, an assessment of the impact of the inquiry-based approach on students' ability to design, execute, and interpret the findings was only based on written reports.

Similarly, Tsapalis' and Gorezi's (2005) study although inquiry, it involved a project in which students had to work on a given topic in groups for a half-semester. However, the environment does not reflect a normal classroom experience; rather it is project-based. Although Lucas' and Rowley's (2011) study had the potential to provide students with experience of inquiry-based learning environment by determining and interpreting the spectra of compounds, students were only provided with spectra based on hypothetical scenarios; rather than interacting with materials, preparing the samples, and running the spectra on their own.

Content Relevance in Science Curriculum

Many educators view content relevance as one that has immediate and future impact on students' life in terms of making them fit in the society and the world at large. However, the issue of relevance has been viewed as a subjective judgment (Hofstein, Eilks, & Bybee, 2011). According to Hofstein et al. (2011), the issues considered relevant to curriculum developers and teachers may be irrelevant to students. Based on the literature, there is no consensus definition for content relevance; however, educators and educational agencies have attempted to provide descriptions of what a relevant or good content capable of promoting meaningful knowledge for one to thrive in the modern world should look. For instance, Keller (1987) described relevance as a way of increasing student motivation towards learning. He delineated six main strategies that promote relevance for motivation in classrooms: (1) experience – using the learners' pre-existing

knowledge and skills; (2) present worth – informing the learners about the impact of the learned material in their current lives; (3) future usefulness – informing the learners about the impact of the learned material in their tomorrow's lives; (4) needs matching; (5) modeling – using role models (e.g., a human figure) of what students want to become; and (6) choice – providing students with an opportunity to own the learning in which they can pursue their work by employing different strategies (Keller, 1987).

Gibbons (1998) viewed the relevance of the 21st century education offered in the higher institutions of learning in terms of outputs, the contribution of higher education to national economic development, and improvement of the quality of life (Gibbons, 1998). In reference to chemistry education, Van Aalsvoort (2004) presented four different categories of relevance that chemistry education should strive to achieve: (a) personal relevance – chemical education must make connections to students' lives; (b) professional relevance – chemical education should reflect possible professionals that students can venture into in the future; (c) social relevance – chemical education should clarify its role in addressing human and social issues; (d) personal/social relevance – chemical education should prepare students to be responsible future citizens (Van Aalsvoort, 2004a).

Others view a relevant science curriculum as one that incorporates socioscientific issues that are pertinent to society (Hobson, 2001; Holbrook & Rannikmae, 2007; Kolsto, 2001; Marks & Eilks, 2009; McPhearson, Gill, Pollack, & Sable, 2008; Preczewski, Mittler, & Tillotson, 2009), while others view content relevance as one that has applications to student's everyday life (Holbrook, 2005; Kolsto, 2001). Holbrook further argued that the relevance of a course should go beyond the simple inclusion of social

issues – it should also seek to promote student attitudes towards the learning of science (Holbrook, 2005). Van Aalsvoort's (2004) description of content relevance is adopted in the current study.

The Perspective of Content Relevance in Schools and Colleges

Despite the NRC's push for meaningful science content in schools, the U.S. has continued to trail other developed countries across the world in mathematics and science. In particular, the recent 2009 results of the international comparative assessment on science and mathematics, that is, *Trends in International Mathematics and Science Study* (TIMSS) and the *Program for International Student Assessment* (PISA) revealed that the U.S. ranked position 10 out of 11 on the performance of 15 year-olds (high school students) with a science mean score of 502 – slightly above the science mean score (501) of international member countries of the Organization for Economic Co-operation and Development (OECD) (OECD, 2011).

The blame on irrelevant curriculum is not only directed to the science curriculum in the U.S., but also in other developed countries. According to Marks and Eilks (2009), a scrutiny of the science curriculum in German indicated unpopularity of chemistry classes in high school level. This resonates with the U.S. curriculum in which students are exposed to 2 years of chemistry, with others not experiencing chemistry at all. Even with the few chemistry lessons offered, they are dominated by the content-driven approach (Hofstein et al., 2011; Marks & Eilks, 2009; Preczewski et al., 2009). Preczewski et al. (2009) pointed the need to shift the focus from science content knowledge to stressing the process and interaction with science in day-to-day life.

According to Hofstein et al. (2011), the content of school science and the pedagogical approaches used do not match with the interests and needs of students and the society—“most students do not find their science classes interesting and motivating” (p. 1459). While the main goal of science education is to prepare scientifically literate future citizens (NRC, 1996), many students remain scientifically illiterate and unaware of science outside the classrooms (Preczewski et al., 2009). The overemphasis on content knowledge, and failure to orient science curriculum toward relevant applications to a student’s life and the society result to “inert knowledge that is only connected to the context of being part of the ‘school science’” (Hofstein et al., 2011, p. 1460).

Preczewski et al. (2009) conducted semi-structured interviews with 7 German and 5 U.S. high school students on their perspective of the process of making meaning of science in everyday life. The participants were selected from three schools that represented urban and suburban areas. Their findings revealed that nearly all the 12 participants (10 of 12) expressed unawareness of science in their daily experiences—they only expressed science behind a concept when they felt a need to understand or explain the science (Preczewski et al., 2009). These authors noted a major difference between the U.S. and the German students, particularly on motivation for understanding or knowing science. While the German students (6 out of 7) expressed personal responsibility for the knowledge of science, the U.S. students’ knowledge of science had to be elicited by external situations such as “parent”, “museum”, among others.

According to Preczewski et al., all the participants viewed engagement as a way of constructing science meaning making in their daily lives. Most of the U.S. students (3 out of 5) expressed meaning of science in everyday life by referencing and explicitly

mentioning the scientific method taught in schools. In contrast, no German student mentioned scientific method; rather they expressed science meaning making in everyday life by referencing their interactions with the natural setting (e.g., their gardens). The authors pointed out that none of the U.S. students mentioned natural setting in making meaning of science in their daily experiences. Preczewski et al. argued that while basic scientific knowledge is goal for science education, all the participants did not value scientific knowledge in constructing science meaning in their daily lives. They emphasized the need for the incorporation of environmental situations in the science curriculum to promote scientific literacy in the U.S..

Other educators have also criticized the state of chemistry curriculum and instruction in schools and colleges. Holbrook (2005) lamented that chemistry teaching in schools and colleges has for long emphasized content knowledge; rather than emphasizing issues and concerns within society—meaningful learning. He argued that science teaching in schools and colleges has for long emphasized “*Science through Education*” rather than focusing on “*Education through Science*”. According to Holbrook, “Science through Education” is content-driven, with content knowledge being the main focus, while “Education through Science” prioritizes issues and concerns within society. Holbrook challenged educators to shift the focus from the former to the latter, that is, towards making chemistry teaching relevant in the eyes of the student (Holbrook, 2005).

Gilbert (2007) summarized 5 major problems facing chemistry education in schools and colleges. A description of these problems is articulated below.

- 1) *Overloaded content*— resulting in aggregation of isolated facts with the focus being broader coverage of concepts; rather than in-depth coverage of the concepts. In other words, “a mile wide and an inch deep curriculum.”
- 2) *Isolated facts*— chemistry curriculum is taught without students knowing how they should form connections within and between the aggregations of isolated facts. This leads to low engagement in classes and poor retention of material thereafter— students do not develop mental schema.
- 3) *Lack of knowledge transfer*— students fail to solve problems using the same concepts they learned in class when presented in different ways; rather they solve problems in ways that closely mirror the ways in which they were taught.
- 4) *Lack of personal relevance*—chemistry rarely reflects the students’ personal relevance.
- 5) *Lack of balanced curriculum*— more focus on content-knowledge and little emphasis on scientific literacy (Gilbert, 2006).

Proponents of content relevance argue that meaningful learning that lead to scientific literacy can be achieved by incorporating socioscientific issues (SSI) (Hobson, 2001; Holbrook, 2005; Holbrook & Rannikmae, 2005; Marks & Eilks, 2009; McPhearson et al., 2008; Zeidler, Sadler, Simmons, & Howes, 2005), implementing curriculum tailored around science, technology, and society (STS) (Cajas, 2001; Yuenyong & Narjaikaew, 2009); and contexts that reflect everyday experiences of students, for instance, in chemistry (Bennett & Lubben, 2006; Gilbert, 2006; Gutwill-Wise, 2001; Korolija, Plavsic, Marinkovic, & Mandic, 2012; Pringle & Henderleiter, 1999; Schwartz, 2006; SENCER, 2009; Weidenhamer, 1997). While SSI and STS are effective

approaches to enhancing content relevance, only context-based curriculum approach is relevant in the current study. The subsequent section discusses the literature on context-based approach in chemical education.

Context-Based Learning (CBL) in Chemistry Education

Following criticism on the ineffectiveness of chemistry education in preparing future citizens, some curriculum developers have attempted to adopt context-based approach to promote meaningful learning. This section discusses context-based learning as a path towards making chemistry relevant to both high school and college students. Prior to embarking on the literature review, it is important to provide the meaning of context-based learning (CBL).

Context-based learning stemmed from the word “context”, derived from Latin language the verb ‘*contexere*’ – meaning “to weave together” (Gilbert, 2006). Although there are various descriptions of context-based learning in the literature, there is consensus in the science education community that CBL involves a curriculum designed to incorporate a ‘context’ or ‘a situation’ that has a real-world connection or application with the goal of making the learning meaningful to students. A recent definition of CBL in the case of chemistry is provided by King (2012). She defined a context based approach in chemistry as follows:

A context-based approach is when the ‘context’ or ‘application of the chemistry to a real-world situation’ is central to the teaching of the chemistry. In such a way, the chemical concepts are taught on a ‘need-to-know’ basis; that is, when the students require the concepts to understand further the real-world application. (King, 2012, p. 53)

A number of chemical educators have attempted to describe context-based learning in relation to its implementation. Fechner (2009) summarized four main characteristics of context-based approach:

- a) *Contexts dictate the content*— real world contexts are chosen as main topics or themes in which curriculum is structured according to the themes, rather than focusing on the content knowledge.
- b) *Need-to-know*— the contexts chosen as themes require specific content knowledge. They should elicit the students' need to know the science content linked to the context.
- c) *Drip-feed*— context approach should provide a possibility of constructing knowledge structures in a cumulative way, in which students can learn concepts through repeated exposure to different dimensions of the concept while allowing them the opportunity to deeply internalize the concepts. The level of complexity of the concepts to be learned change from one encounter to the next.
- d) *Student-centered methods*—the contexts should engage students in active knowledge construction, with real world issues used to evoke meaningful knowledge construction (Fechner, 2009).

A few countries, U.S., U.K., Israel, Germany, and Netherlands, have attempted to embrace context-based curriculum approach, even though there is little evidence that many schools and colleges in these countries have implemented this approach.

Context-Based Learning in the U.K.

The implementation of context-based chemistry curriculum began in the early 1980s with the development and implementation of Salters courses in the U.K. (Bennett & Lubben, 2006). The approach “Salters approach” was named after the funder of the context-based approach. Teachers and science educators met at York, in U.K. to discuss the approaches of making chemistry relevant to students through the proposed Salters approach. The general fundamental goals of Salters courses are to promote students’ appreciation of how chemistry: “contributes to their lives or lives of others around the world; or helps them to acquaint a better understanding of the natural environment” (Bennett & Lubben, 2006, p. 1001). The courses cover science areas such as chemistry, biology, and physics, and have been implemented in secondary and pre-university levels in England and Wales (Bennett & Lubben, 2006). The Salters courses include:

- 1) Chemistry: the Salters Approach—developed in the mid 1980s for 14-16 year-old students;
- 2) Science: the Salters Approach—developed in the late 1980s for 14-16 year-old students;
- 3) Salters Science Focus—developed in early 1990s for 11-14 year-old students;
- 4) Salters Advanced Chemistry—developed in early 1990s for 17-18 year-old students;
- 5) Salters Horners Advanced Physics—developed in the mid to late 1990s for 17-18 year-old students; and
- 6) Salters Nuffield Advanced Biology—being developed for 17-18 year-old students (Bennett & Lubben, 2006).

According to Bennett and Lubben, the four specific aims of the Salters Advanced Chemistry are to: show how chemistry fit in the world and in the work that chemists do; show the relevance of chemistry to people's lives; broaden the range of teaching and learning activities in chemistry; and present chemistry in a way that stimulate and challenge a wider range of students. Salters Advanced Chemistry is currently offered in both modular and textbook forms (Bennett & Lubben, 2006).

A relevant study pertaining experiential evaluation of Salters Advanced Chemistry curriculum was conducted by Key in 1998 in England, in which she examined the change of students' perceptions of chemical industry during 2 years of exposure to Advanced Chemistry course. Her study involved 1, 200 students— from 3 conventional advanced-level course (treatment group) and the Salters Advanced Chemistry course (control group). Her findings indicated that the treatment group showed more appreciation on the importance of chemical industry (the subject-matter in both groups) than the control group (cited by Bennett & Lubben, 2006).

Context-Based Curriculum in the U.S.

In the U.S., the development of context-based curriculum, particularly in chemistry was initiated and sponsored by the American Chemical Society (ACS) and the National Science Foundation (NSF) (Schwartz, 2006). Examples of the most popular context-based texts and modules in the U.S. schools and colleges are discussed below.

ChemCom: Chemistry in Community—developed in 1988 by Schwartz et al. for high school and first year non-science majors at college level. The units incorporate student-centered approach with chemical principles introduced on a need-to-know basis.

Recent editions have been revised to address the NSES. Over 500, 000 copies have been disseminated, in which 2 million U.S. students are reported to have learned from the text. The text also appears in Russian, Spanish, and Japanese languages (Schwartz, 2006). An evaluation published in 2004 by the National Center for Education statistics showed an increase in student enrollment in formal chemistry courses following exposure to *ChemCom* curriculum, that is, from 32% in 1982 to 62% in 2000 in the U.S..

Chemistry in Context (CiC)—developed in 1994 by Schwartz et al. for undergraduates (non-science majors). The goals of CiC considered during the development were to:

- 1) Promote student interest towards chemistry and relevance to society;
- 2) Enhance understanding of chemistry concepts;
- 3) Show significance of both theoretical and practical chemistry;
- 4) Develop analytical and critical skills, as well as the ability to assess risks and benefits from a given information;
- 5) Provide students with hands-on experience with chemical phenomena; and
- 6) Equip them with the ability to locate and address technical issues (Schwartz, 2006).

Thirteen chapters were published in the first CiC edition which comprised of the following titles in the order:

The air we breathe; Protecting the ozone layer; The chemistry of global warming;
Energy, chemistry, and society; The wonder of water; Neutralizing the threat of acid rain;
Onondaga Lake – a case study; The fires of nuclear fission; Solar energy – fuel for the

future; The world plastics and polymers; Designing drugs and manipulating molecules;
Nutrition – food thought; The chemistry of tomorrow. (Schwartz, 2006, p. 985)

A study on the evaluations of CiC curriculum was conducted in 1990-91 by three of the textbook authors (Nakhleh, Bunce, & Schwartz, 1995) in the authors' institutions (cited by Schwartz, 2006). According to Schwartz, the study sought to examine: students' opinions towards chemistry after studying CiC. A Likert scale-based instrument consisting of 20 statements on students' beliefs about chemistry was administered to non-science majors enrolled in CiC-based courses in 9 colleges and universities in 1991. A comparison study was also conducted with students subjected to CiC texts and those using normal texts.

Findings indicated that students in 3rd and 4th year in the undergraduate program displayed a greater positive attitude change to the CiC approach in comparison to 1st and 2nd year students. According to Schwartz, such difference could be due to student maturity in the learning, in which students in the advanced levels are likely to “gain most from the risk-benefit analyses and critical thinking” (p. 990). Such hypothesis has, however, not been tested in which students in the advanced groups have been compared with those at lower levels with regards to attitude and perceptions about learning. Findings also indicated similar attitudes for both control and treatment groups.

Science Education for New Civic Engagement and Responsibilities (SENCER) — was established in 1989 (SENCER, 2009). SENCER was established with the main goal of equipping students with abilities in science, technology, engineering, and mathematics (STEM). The main aims of SENCER curriculum are to attract “more students interested

and engaged in learning; to help students connect learning to their other studies; and to strengthen students' understanding of science and their capacity for responsible work and citizenship". The development of SENCER courses and programs was motivated by the belief that "improved intellectual capacity originates and develops within a student's interest and motives" (p. 6).

According to SENCER, this can be enhanced by tailoring the learning around real issues of civic importance and by taking into consideration that learning is the construction of knowledge by the individual— "mediated by the context of the learning, by the social environment, and by the prior knowledge of the learner" (SENCER, 2009, p. 6). The program was developed mainly for non-science majors and comprises of 19 courses, modules, case studies, learning communities, and field programs. The pedagogical strategies include authentic learning, teamwork, and scientific inquiry. The titles of the courses include: "Chemistry and Ethnicity: Uranium and American Indians", and "Biomedical Issues of HIV/AIDS", and "Forensic Investigation: Seeking Justice Through Science" (cited by Schwartz, 2006, p. 995). Overall, the courses emphasize interdisciplinary connections (SENCER, 2009)

Chemistry: The science in context—developed in 2004 by Gilbert et al. (Cited by Schwartz, 2006) for science majors (tertiary). According to Schwartz (2006), although the title is context-oriented, the text book is not context-driven; rather it is comprised of many embedded examples of context. Themes are applied in each chapter title, for instance, "Molecular Shape and Greenhouse effect" (Chapter 7) (cited by Schwartz, 2006). Concept Tests are used to probe students' conceptual understanding, while

marginal notes are employed to link connections to other concepts in the text (Schwartz, 2006).

Chemistry—developed in 2005 by Bell et al. for science majors (tertiary) through ACS funding. Overall, the contexts in the text are presented through biological systems, which, in turn are used to explain a chemical principle (Schwartz, 2006). According to Schwartz, the text contains 11 long, and detailed concept-rich chapters that are presented in a logical sequence. Moreover, student-centered activities included in the text are “Investigate This”, “Consider This”, and “Check This” (Schwartz, 2006). No assessment of students has been reported based on this text.

ChemConnections modular materials—These materials were developed by a team of Modular Chemistry Consortium and the ChemLinks Coalition with the support of the NSF systematic Change Initiative in Chemistry Education for the U.S. undergraduate students (ChemConnections, 2002; Cited by Schwartz, 2006). The goals of the modules are to enhance the learning and appreciation of chemistry while promoting an understanding of chemistry concepts, and development of scientific knowledge and skills necessary to prepare students for progression into chemistry programs and in making informed decisions in society (ChemConnections, 2002; Gutwill-Wise, 2001). Real-world topics are used as a vehicle to teach chemistry concepts. For example, the topic: “*Why does the Ozone Hole Form?*” is a module in which the world wide web is employed to teach about the structure of the atmosphere and the ozone layer, when the ozone hole is formed, and its current status. Chemical concepts emphasized include: oxygen chemistry, and chemical kinetics (ChemConnections, 2002). The modules are designed around students-centered activities and collaborative group learning.

A follow-up study on the impact of modular approach by Gutwill-Wise (2001) indicated that Modular classes had a better understanding of chemistry concepts than their counterparts in the non-Modular classes. Modular students outperformed the non-modular students on in-class exams/concept tests and on problem-solving interview questions, and had more positive attitudes towards chemistry than non-modular students. However, the Modular approach was not well received by the students. Students showed negative attitudes towards the Modular approach and the experimental design. They also experienced a mismatch between the realities of the Modular approach and chemistry concepts. Consequently, the overall positive attitudinal score was lower for the Modular group than the non-Modular.

Beer as a Teaching Aid—This module was recently developed and implemented by Korolija et al. (2012) for upper-level high school chemistry students (18-19 years-old) in Serbia, California, U.S.A. Beer is used as a context for teaching chemical concepts such as “solubility, solution, heterogeneous and homogenous mixtures, filtration, pH, indicators, chemical reactions for identification of different chemical compounds, chemical equilibrium, chemical interactions, fermenters” (Korolija et al., 2012, p. 605). Six main questions are used to organize the module include: “What makes Beer so Popular and Timeless? Is it because of [:]

- its refreshing effect or its unique taste?
- its low alcohol content?
- its nutritional value?
- the presence of substances essential for the normal functioning of our body?
- the presence of protective free radical scavengers?

- the lower price than the other alcoholic beverages?” (p. 606)

Students formulate hypothesis, devise experiments with the teacher’s guidance, execute the experiments, analyze the results, test their hypothesis, and solve relevant problems. Following the investigations, discussion prompts are used to probe students’ critical thinking on the concepts (Korolija et al., 2012). The authors do not report any information about the evaluation of this module on impact of student outcomes.

Another example of context-based modules tailored around chemistry has been reported by Pringle and Henderleiter (1999). The modules are based on modified traditional experiments for analytical chemistry students at the college level. According to the authors, seven of the nine conventional analytical laboratory experiments were modified, and one new experiment designed, to incorporate a context-based approach. The new and modified experiments involved a “script” or “real-life” scenario that provided a rationale for learning the laboratory techniques and methods. In particular, the new experiment involved “determination of total dissolved solids in a community water sample.” According to these authors, the modified activities were designed around “a context, reason why an analysis of this nature may be performed” (p. 101). The modified experiments also incorporated questions that challenged students to make decisions about the scenario prior to the laboratory, and provide a rationale for solving the problem using their results.

Students worked individually except for one experiment where they worked in a group to solve a problem. For some modified experiments, students were required to share data. The study was conducted at the University of Northern Colorado. A control group (21 students) exposed to traditional experiments, and a treatment group (36

students) exposed to the context-based modules were involved in the study. Findings indicated that all the groups felt competent, aware and able to perform the techniques expected of them. According to the authors, the control group made more statements relating to laboratory techniques and skills, and applications outside of classrooms than did the treatment group—none of the students from the experimental group expressed these experiences.

Moreover, a majority of the students from the experimental group (7 out of 10 students interviewed) indicated that although they learned from the experience, they did not enjoy some of the context-based experiments. Additionally, the experimental group expressed more expectations that were not fulfilled by the laboratory course. However, students from this group expressed more confidence about their self-perceived abilities, reasoning and metacognition, familiarity, and general concept knowledge than control classes (Pringle & Henderleiter, 1999). Overall, the authors contended that:

None of the data strongly support or refute the belief that students enrolled in first-semester analytical chemistry classes will develop a better understanding of how practices and techniques associated with analytical chemistry can be applied to many areas of chemistry and to science in general. (p. 105)

Other examples of context-based modules and texts implemented in other countries based on the literature are presented in Table 2.2. In summary, I have discussed how context-based approach to teaching and learning has been implemented in a number of countries to address the issue of irrelevant chemistry curriculum in schools and universities. I have also presented examples of context-driven curriculum, as well as the existing studies on the effectiveness such curriculum on student outcomes, particularly the affective domain.

Table 2.2 Context-based modules Implemented in Israel, Germany, and the Netherlands

Context-Based Topic and Country Implemented	Level	Description
Industrial Chemistry (IC)—Israel (1980s)	Tertiary- first years	The goal is to make chemistry relevant by utilizing the context of industrial chemistry. Materials are implemented in the form of case studies. Emphasis is placed on the applied chemistry and the socioeconomic and environmental consequences (Hofstein et al., 2011; King, 2012; Pilot & Bulte, 2006). The content include: industrial production process, and products and their uses (Pilot & Bulte, 2006).
Chemie im Kontext (ChiK)- Germany	High School – upper and lower levels	Curriculum enacted through “symbiotic approach”—group of science educators and teachers selected, and developed the units, which vary from one state to another (King, 2012). Main topics include: daily situation, societal issues, scientific and technical issues (King, 2012).
Chemistry in Practice (ChiP)—Netherlands	High School	The goal is to make meaningful connections of chemistry to students’ daily lives and societal issues. The context-based curriculum is designed on the need-to-know principle (Pilot & Bulte, 2006).

Based on the existing literature, studies on the effects of context-based chemistry curricula on student affective domain are few, and the existing ones are over a decade old. Although the existing evaluation studies show some positive and negative impacts of context-based curriculum on the students’ affective domain, more empirical research work in this area is needed to validate the arguments on the findings reported in the aforementioned evaluation studies.

Nanoscience and Nanotechnology Education

In 2000, President Clinton established the National Nanotechnology Initiative (NNI), a multi-agency in the U.S.A government program that coordinates federal efforts in nanotechnology. Meyya Meyyappan describes nanoscience as a facet of science that deals with the understanding of, and the discovery of nano materials and their properties as well as their practical utility (Meyyappan, 2009). He describes nanotechnology as having a *“specific demonstration of a product or process incorporating all the learnings from Nanoscience and addressing all the usual issues of technical feasibility, functioning of that product in real-world conditions, reliability, robustness, and a pathway to manufacturing”* (p. 4).

According to the NNI (2011), nanoscience involves research to discover new behaviors and properties of materials with dimensions at nanoscale—from 1 to 100 nm while “nanotechnology is the understanding and control of matter at dimensions between 1 to 100 nanometers, where unique phenomena enable novel applications” (p. 3). The NNI adds that “encompassing nanoscale science, engineering and technology, nanotechnology entails imaging, measuring, modeling, and manipulating matter at this length scale” (p. 3). The NNI (2011) added that “interests in nanotechnology arise from its potential to significantly impact several fields such as aerospace, agriculture, energy, the environment, healthcare, information technology, homeland security, national defense, and transportation systems” (p. 4). The unique size-dependent properties of the nanoparticles make them super-ordinate and indispensable in the society. In particular, synthesis of nanoparticles, ranging from 1–100 nm, has proved to have potential applications that can solve the challenging issues in contemporary society (NNI, 2011).

In the subsequent sections, I discuss the literature behind nanotechnology education in schools and colleges.

Implementation of Nanoscience and Nanotechnology Education

One of the NNI (2011) goals and vision is to “*develop and sustain educational resources, a skilled workforce, and the supporting infrastructure and tools to advance nanotechnology*” (p. 4). With the current advancement in nanotechnology, institutions are beginning to embrace the development and implementation of nanoscience and nanotechnology curricula, which will adequately prepare students as future nanotechnologists. The National Center for Learning and Teaching (NCLT) Nanoscale Science and Engineering, an interdisciplinary center for teaching and learning established and supported by NSF since 2004, in collaboration with researchers and educators from a number of research universities such as Northwestern, University of Michigan, University of Illinois (Urbana and Chicago), Purdue, Notre Dame, among others, formulated the “big ideas” to be considered in teaching Nanoscience and Nanotechnology for grades 7-12 and grades 13-16 (Stevens, Sutherland, Schank, & Krajcik, 2009).

The big ideas for 7-12 include: *Size and scale, Properties of matter, Particulate nature of matter, Modeling, Dominant forces, Tools, Self-assembly, and Technology and Society*. Big ideas for 13-16 include: *Size and scale, Size dependent properties, Tools and instrumentation/characterization, Models and simulations, Surface dominated behavior, Self-assembly, Surface-to-volume ratio, Quantum mechanics, and Societal impact and public education* (Stevens et al., 2009).

Preparation of Teachers for the Nanoscience and Nanotechnology Education

Teachers and educators have heeded to the NNI's call of preparing future technologists by developing curriculum that is centered on the proposed big ideas in nano. The first target audience for these big ideas has been the middle- and high school teachers, especially in the U.S.. Nanoscience and nanotechnology being a booming scientific field, most middle-and high teachers lack knowledge in this field (Healy, 2009). In the past decade, the goal of the NCLT has been to strengthen the push on training and equipping the middle-and high school teachers with knowledge and skills on the nanoscience and nanotechnology concepts through professional development teacher programs.

Consequently, some educators in the U.S. have taken the lead in educating teachers about the nanoscience and nanotechnology concepts through diverse approaches such as workshops, seminars (Daly & Bryan, 2007; Daly, Hutchinson, & Bryan, 2007), and online courses (Tomasik, Jin, Hamers, & Moore, 2009). These researchers and educators report the teachers' conceptual understanding of the nanoscience and nanotechnology concepts during and/or after attending the professional development programs. Recent publications on nanoscience and nanotechnology education also indicate that universities are considering the incorporation of nanoscience and nanotechnology concepts into the undergraduate science programs (Furlan, 2009; Moyses, Rivet, & Fahman, 2010; Mulfinger et al., 2007; Sharma, Gulati, & Mehta, 2012), as well as science graduate programs (Blonder, 2011).

The incorporation of Nanoscience and nanotechnology has not been embraced only in the U.S.. The National Science Council in Taiwan also established a

nanotechnology program for K-12 teachers (Lee, Wu, Liu, & Hsu, 2006). The study reported by Blonder (2011) may also be an indication that nanotechnology education is being integrated in some schools and colleges curriculum in Israel. Lee et al. (2006) conducted a longitudinal study (for about two years) with 193 teachers from 169 middle- and high schools in Taiwan. The goals of these authors' study were to help teachers overcome fear of learning about nanotechnology, and to equip them with knowledge about the new technology. The teachers participated in five regional programs, mainly workshops, offered in 2004. The workshops focused on topics such as: "the physical phenomena of the nano world; atoms, molecular and nanotechnology; preparation and application of nano materials; making carbon nanocapsule and carbon nanotube models; making nano solar cells; and the application of nano particles in biomedicine" (p. 142). According to the authors, the participants completed a survey instrument at the annual conference in November 2004.

Findings indicated that teachers' attitudes and interests in learning nano-related concepts increased over the period of involvement in the programs. About 90% indicated that their interest in learning new technology increased (Mean = 4.2); and 85% felt that they became more interested in learning their own subjects (Mean = 4.17) as well as other subject areas (Mean = 4.17). However, teachers without chemistry and physics backgrounds experienced difficulty in grasping the concepts of nanotechnology. Also, junior high school teachers experienced hardships in understanding the nanotechnology concepts than senior high school teachers.

Tomasik, Jin, Hamers, and Moore (2009) from the University of Wisconsin-Madison designed an online professional development course on Nanoscience and

Nanotechnology for middle-and high school teachers. The eight-week course addressed the following topics and in order in which they are presented: (1) introduction to nanoscience, (2) the nanoscale, (3) properties of nanomaterials, (4) measuring nanoscale structures, (5) synthesis of nanomaterials, (6) health and environmental effect; nanotechnology and medicine, (7) nanomaterials and nature, and (8) societal impacts (Tomasik et al., 2009). According to the authors, the goal of the course was to familiarize the teachers with nanoscience concepts as well as promote the incorporation of nanoscience into their curriculum. Findings indicated that teachers showed significant learning gains on nanoscience concepts, and were successful in developing modules for use in their classroom following the online nanoscience and nanotechnology course. Nonetheless, teachers stated that the actual nano course was lacking in relevance, cognitive demand, peer support, and interpretation of meaning between in comparison to their expectations prior to the course.

Nanoscience and Nanotechnology in Undergraduate and Graduate Curriculum

While the literature documents a few empirical studies tailoring around nanotechnology professional development programs for middle- and high school teachers, there are no empirical studies that focus on non-teacher students and Nanoscience and nanotechnology at the undergraduate level. A few seminal studies have been documented on the incorporation of nanoscience and nanotechnology into undergraduate and graduate science programs (Furlan, 2009; Moyses et al., 2010). This does not imply that nanotechnology is not being embraced by colleges and universities. In fact, it is documented that some universities are offering either graduate or

undergraduate courses on nanotechnology (Uddin & Chowdhury, 2001). Examples of such universities include, but not limited to Clarkson University, Clemson University, Cornell University, Penn State University, Rice University, University of Washington, Virginia Commonwealth University, State University of New York at Buffalo, and Rensselaer Polytechnic Institute. Recent publications of classroom experiments focusing nanoscale concepts in undergraduate science programs are also an indicator that nanotechnology education is taking shape in colleges and universities.

Furlan (2009) study indicates a successful implementation of nanoscience and nanotechnology concepts in the first and second year chemistry curriculum. The author evaluated the effectiveness of the program by administering a pre-and post- quiz and a survey to 60 participants. According to Furlan, students' increased knowledge and awareness of nanoscience and nanotechnology as evidenced by the increase in quiz scores from 0-50 % (pre-treatment) to above 70% (post-treatment). Moreover, the analysis of the survey responses revealed that Nanoscience concepts motivated the participants to learn chemistry concepts; improved students' skills in the use of sophisticated instrumentation such as Scanning Tunneling Microscope (STM); and improved students' attitudes towards chemistry. Furlan contended that hands-on approach provided students with the opportunity to develop observation and reflection skills on nanoscience and nanotechnology concepts (Furlan, 2009).

Moyses et al.'s (2010) study involved 10 students enrolled in a 3-hour credit, lecture-based course— Introduction to nanotechnology, at Central Michigan University. The class met once a week, over a period of 4 weeks. The course covered the following topics: (1) Week 1 — defining nanotechnology; (2) Week 2 — applications for

nanotechnology; and (3) Week 3 — an overview of the health hazards and ethical considerations of nanotechnology. In Week 4, students took a final exam that tested their knowledge on the above topics.

Evaluation of the nano course indicated that nonscience majors experienced difficulties in understanding nano concepts, as well as their applications in modern society. Students' pre-survey responses on the nanotechnology applications revealed that science majors listed applications related to their field, whereas nonscience majors did not offer any applications. For instance, a meteorology majors stated nanotechnology applications in "meteorological radar and modeling tornadoes"; the chemistry major stated applications in developing "more efficient solar panels; IT major listed applications in "faster computers" or "faster/better circuits"; and "endless possibilities related to healthcare environmental work" (biomedical science major) (p. 286).

Blonder (2011) reported findings on the development of nanochemistry course, an advanced course for chemistry teachers in Israel. The course, Introduction to Materials and Nanotechnology, was part of a special M.Sc. program for science teachers offered in Rothschild-Weizmann program for Excellence in Science Teaching. The nanotechnology course was designed to incorporate both lecture part and laboratory experience. According to Blonder (2011), the goal of the course was to provide high school teachers with basic concepts and content knowledge in nanoscience, to promote their enthusiasm for modern chemistry and its applications, as well as prepare them to teach advanced topics in nanochemistry.

Eight participants (7 high school teachers and one M. Sc. Chemistry student) took the course. The nano related modules included: *qualitative quantum mechanics*;

Characterization methods; Selected advanced topics in materials science and nanotechnology; Research Lab Experiments— Drawing with nanotubes and Electrospinning nanotube-reinforced composites experiments; and Connection to Education.

The evaluation for the course indicated that some students were enthusiastic about the course, while others were anxious (Blonder, 2011). Participants showed significant improvement in conceptual understanding of nanochemistry ($p < 0.05$). Overall, blonder argued that the course provided the students with basic knowledge and skills considered important for nano literacy.

Summary

This section has discussed the development and implementation of the “Big Ideas” of nanotechnology in the K-16 education system in the U.S.. I have also presented the literature surrounding the implementation of nanotechnology educations in schools and universities in and outside the U.S.. Based on this literature, it is clear that nanotechnology has been introduced in schools and universities as a single discipline; rather than an interdisciplinary field. Therefore, it is not surprising that teachers and undergraduate students exposed to nanotechnology concepts expressed knowledge gaps in integrating nano concepts in the lesson plans, and in grasping the concepts, respectively.

Chapter Summary and Remarks

I began this chapter by presenting a brief history of how laboratory work and instruction transformed from European countries to American Academies, and eventually into public schools, and colleges and universities in the U.S.. I also articulated the aims and goals of laboratory work as perceived by researchers and educators. One of the things that caught my attention is that although affective domain components (e.g., attitudes towards science) are among the key aims the laboratory work and instruction should strive to promote, faculty pay little attention to this goal even when students value it as the most important in laboratory work. Promoting student interest and positive attitudes towards science is one area that science programs, including chemistry should step up on, for such will not only enhance high performance in the courses, but will ensure student progression into science careers. One way to promote student interest and positive attitude is to develop curricula that have relevance to real-world applications, and that will engage students to be active participants in the classroom rather than passive listeners.

A review of students' perceptions and attitudes towards chemistry at college level indicated that most of the studies have been done in the U.K and few in Turkey. However, little is known about students' attitudes and perceptions towards chemistry, particularly for students enrolled in both lower and advanced chemistry courses in the U.S.. Universities in the U.S. experience under enrollment in science programs for science majors compared to courses in humanities (e.g., Seymour & Hewitt, 1997). Lack of interest and inapplicability of the content to students' daily-lives have been highlighted as some of the key factors for under enrollment and attrition in science programs

Seymour & Hewitt, 1997). It is therefore important that studies focusing on student perceptions and attitudes towards science courses be conducted in the U.S. to understand the possible causes of negative attitudes towards science programs. Till then will under enrollment and attrition remain a major problem in the U.S. universities and colleges. Based on the reviewed sub-topics in this chapter, research pertaining perceptions and attitudes towards chemistry for students enrolled in advanced chemistry courses has been neglected. I reiterate Kerr's claim that: "*further learning is more likely to take place if interest develops as knowledge increases*" (p. 25); therefore, it is important to examine student attitudes, and strategies that promote positive attitudes in advanced levels of chemistry, that is, sophomore level and beyond.

Furthermore, the literature revealed that although faculty and teachers set the goals that a course or a lesson should strive to achieve, such goals are rarely achieved in the classroom (e.g., Abraham et al., 1997; Abrahams & Millar, 2008). This problem has been associated with a lack of alignment between the course goals/lesson objectives and the instructional strategy used. Studies on laboratory instruction in chemistry (e.g., Abraham et al., 1997; Domin, 1999; Hilosky et al., 1998) revealed that many universities in the U.S. continue to implement verification style in laboratory settings. Moreover, the few studies documented in the literature on the use inquiry-based approach in the chemistry laboratories and/or classes in colleges and universities in the U.S. is an indicator that this approach is not common in institutions of higher learning.

Furthermore, empirical research focused on the impact of inquiry-based experiments on the perceptions and attitudes of students enrolled in both lower and advanced chemistry courses towards chemistry is very thin. There is a need to examine

the impact of inquiry on the affective domain and perceptions of students towards chemistry, particularly for students enrolled in advanced chemistry courses (i.e., 2nd, 3rd, and 4th years).

Literature on nanotechnology education indicates that the introduction of nano-related concepts in professional development workshops for teachers has proved to be challenging in preparing them to teach nanotechnology education in their classrooms. Such challenges are not surprising, because the curriculum developers appear to have ignored the complexity of these concepts relative to the teachers' abilities. Ideally, expecting middle school teachers to develop a lesson on how they can teach, for example, Ferro fluids to middle-schoolers without in-depth nano related knowledge can be a challenge. The proposed short professional development workshops— packed with several nano topics, are not effective in equipping teachers with adequate knowledge required to prepare future citizens for nano literacy.

Furthermore, nanoscience and nanotechnology concepts have been introduced in schools and universities as a single discipline without integration. This may be another possible reason for the aforementioned challenges as integration of nano concepts with other science concepts, for the most part, appears to have been ignored in teaching these concepts. Basic knowledge in science disciplines is essential for understanding the proposed nano related concepts. Therefore, integrated nano-science curriculum should be adopted into the undergraduate curriculum, in which future teachers can experience the actual content as part of their undergraduate degree. This will eliminate the need for ineffective future professional development geared toward equipping teachers with content knowledge on nano concepts. Greenberg (2009) asserted that challenges

pertaining the integration of nanoscience and nanotechnology concepts in middle-and high schools will continue to be experienced unless the teachers are exposed to nanoscience concepts during their college or undergraduate classes (Greenberg, 2009).

He said:

Until we have a generation of science teachers who are exposed to nanoscience concepts during their college classes, we will need to rely on professional development opportunities to enable teachers to understand nano-scale concepts needed for proper implementation of nanoscience-focused educational materials. (p. 768)

Moreover, most of the reviewed nano studies reported herein have emphasized on students' conceptual understanding of nanoscale science and nanotechnology. However, the impact of nano education on students' affective domains towards learning science has been neglected. Nanoscience and nanotechnology being a novel field that addresses relevant issues in the society, it has potential to positively impact students' attitudes towards science which, in turn, can lead to higher retention rates in science programs, as well as student progression into science careers. Also, incorporating nanotechnology into the existing science curriculum, including chemistry, will not only acquaint students with knowledge of nanoscience and nanotechnology and contribute towards the anticipated workforce in the nanotechnology industry, but will also make the otherwise abstract science concepts visible and relevant to students.

While the advocates of nanotechnology education believe that nano-related concepts can provide authentic experiences for students through scientific inquiry, most of the reported modules implemented in the undergraduate curriculum follow the traditional method of teaching. The use of active teaching strategies such as inquiry-

based and problem-based approaches is likely to promote authentic experiences to students. Although concept mapping is considered an active learning approach, it is not authentic if no real experiments are involved. Most of the suggested “big ideas” in nano are complex, and therefore, students need real experience with the nanoscale phenomena for meaningful learning to occur.

I contend that for effective implementation of nanoscience and nanotechnology in schools and universities, curriculum developers should consider infusing these concepts with other science disciplines; rather than treating them as a single discipline. The implementation of integrated nano-science related concepts should also encompass active instructional strategies such as inquiry-based approach, and laboratory experience for authentic learning. I echo Meyyappan’s argument that:

If nanotechnology is going to be the technology of the 21st century, then we have the obligation to educate the future generation of scientists and engineers about this emerging field. This requires reaching out beyond the master’s and Ph.D. students and including nanoscience and technology in the curriculum at the undergraduate level. (Meyyappan, 2009, p. 5)

The subsequent chapter, Chapter 3, is a discussion of the methodology employed in addressing the research questions previously presented in Chapter 1.

CHAPTER 3 : METHODOLOGY

Introduction

This chapter discusses the research design, the context of the study, participants, data collection methods and procedures, and data analysis procedures to be employed in addressing the aforementioned research questions. Overall, mixed methods approach will be employed in this study. This approach involves the use of both quantitative and qualitative paradigms to address the research questions. In particular, explanatory design, a form of mixed methods (J. W. Creswell & Plano Clark, 2007), will be considered. A detailed description of this design is presented below.

Explanatory Research Design

The current study employed the explanatory design, particularly the “Follow-up Explanations Model” (Creswell & Plano Clark, 2007). The Explanatory Design (also known as the Explanatory Sequential Design) is a two-phase paradigm, which involves the use of qualitative methods to explain quantitative results (Creswell & Plano Clark, 2007). When qualitative methods are employed to expand on the quantitative results, this model is referred to as “*Follow-up Explanations Model*” (Creswell & Plano Clark, 2007). Figure 3.1 shows the implementation steps for the “Follow-up Explanations Model”. The first phase involves the collection and analysis of quantitative data. Based on the quantitative findings, the researcher then identifies the items to be followed up with qualitative data. The selected items can be those statistically significant, non-significant, or interesting to the researcher (Creswell & Plano Clark, 2007). The second phase,

qualitative, follows from the results of the first phase (i.e., quantitative data). The qualitative data collected is analyzed, and the findings used to interpret quantitative findings. Overall, the emphasis is placed more on the quantitative than qualitative methods.

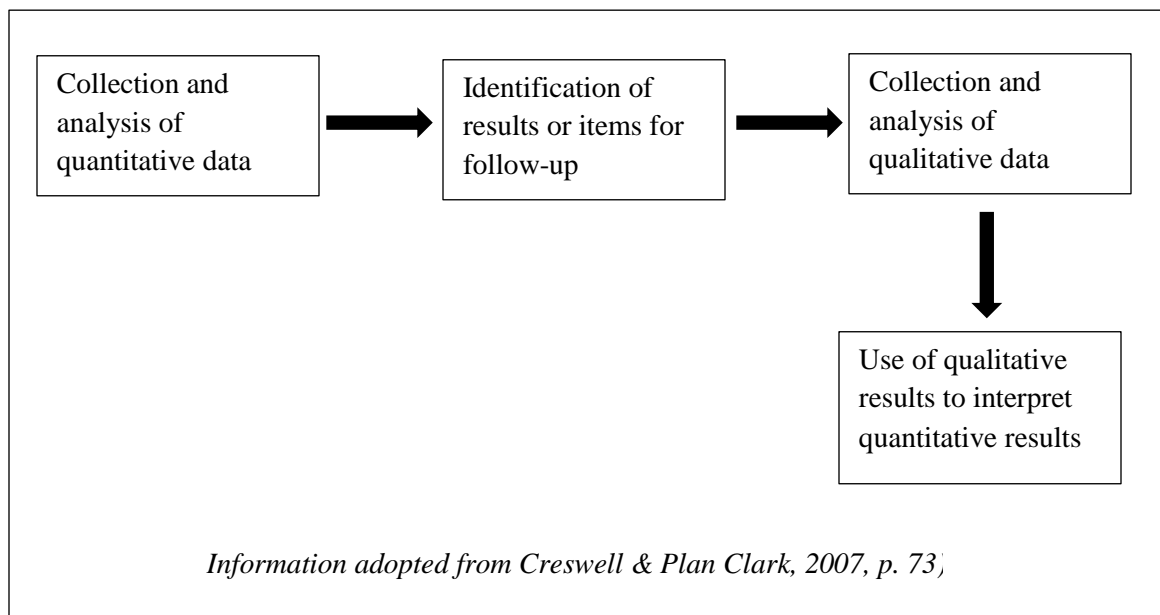


Figure 3.1 Explanatory Design: Follow-up Explanations Model

Research Contexts

The study was conducted in a research-based university in the Mid-West of the United States. Convenience sampling (Creswell, 2003) was employed in selecting this university. An approval to conduct this study was obtained from the Human Subjects Institutional Review Board (HSIRB)—see Appendix C. The two inquiry-based integrated

nanotechnology-chemistry modules were implemented in the 2000 level quantitative analysis chemistry laboratory course (CHEM 2260) in the aforementioned university. The nature of the quantitative analysis chemistry laboratory course offered in the university in question, and the two Nanoscale science laboratory modules are discussed in the subsequent sub-sections. Moreover, a description of the participants involved in this study is provided.

Quantitative analysis chemistry laboratory course (CHEM 2260). This course aims at providing students with opportunities to: appreciate the difficulties involved in the judgment of experimental accuracy and precision of a data set as well as the value of statistic evaluation methods; experience first-hand skills necessary in solving analytical problems quantitatively; use a wide array of analytical chemistry techniques; and develop confidence in laboratory skills and the ability to collect high quality analytical data. It is a 3-credit course, and students meet in the laboratory once per week. Students take this course in conjunction with the lecture-course. Students taking this course come from diverse science programs including chemistry, biochemistry, biology, biomedical sciences, physics, secondary education, among others.

The course is offered in the fall and spring semesters. The conventional laboratory experiments offered this course include: Calibration of glassware, Gravimetric determination of Sulfate, Gravimetric determination of Nickel, Volumetric determination of Soda Ash, Volumetric Determination of Soda Ash Continue, Potentiometric determination of an Acid, Titration of Calcium and Zinc, Photometric determination (UV-Vis spectroscopy) of manganese in steel, Fluorometric determination of Aluminum,

Gas Chromatography (GC) of alcohols, High-Performance Liquid Chromatography (HPLC) of caffeine.

Typically, the experiments follow “cook-book” procedures, in which clear directions are provided in each experiment and reiterated by the laboratory instructor during the pre-laboratory lectures. Therefore, the students’ role is to verify the scientific claims explained or demonstrated by the instructor. In other words, expository method of instruction is employed in which the discussion of expected experimental results precedes the exploratory process. The researcher observed the conventional lab experiments in spring 2012 to get familiar with the analytical techniques used in this course. This was important in ensuring that same lesson objectives, that is, analytical techniques were retained in the new nanotechnology-chemistry modules.

Development and implementation of integrated nanotechnology-chemistry modules. Two conventional experiments (i.e., UV-Visible analysis and GC experiment) were modified to incorporate nanotechnology concepts. The two modules were developed in spring 2012 and implemented in fall 2012. The modules were developed by researcher, under the guidance of one chemistry faculty whose research area is in nanotechnology. The modules were also reviewed by two other chemistry faculty—one faculty was the instructor of record for the quantitative analysis chemistry laboratory course, and the other has a chemistry and science education background. In each module, “big questions” are used to introduce the lesson.

Module #1—Synthesis of Gold Nanoparticles: Analytical Studies on the Chemical Reduction of Gold Ions, and Molar absorptivity Determination of Gold Nanoparticles using UV-visible Spectrophotometer

The two “big questions” that guided the development of this module are: How is nanotechnology important in modern society? How is nanotechnology important in fostering the relevance of chemistry in society? Students were introduced to nanotechnology in which they discussed the different applications of gold nanoparticles in contemporary society such as visualization and bio-imaging; catalysis applications; detection and quantification of contaminants/pollutants; and drug delivery for treatment/tumor destruction, or gene delivery (NNI, 2011).

Prior to the hands-on activities, students were encouraged to develop a procedure for making gold nanoparticles using supplied reagents and equipment. In groups of four, they were also encouraged to discuss and explain the role of the reagents and equipment with minimal guidance from the TA. They then synthesized 4 sets of different gold nanoparticle solutions, during which they studied the reduction of gold ions (from oxidation state +3) to gold nanoparticles (oxidation state 0). Additionally, they ran the 4 sets of gold nanoparticle solutions in the UV-visible spectrophotometer in which they measured the transmittance and determined the absorbance of each gold nanoparticle solution. Additionally, they calculated the concentration of their gold solutions, and determined the molar absorptivity of their gold nanoparticles using the Beer Lambert's Law. A whole class discussion was led by the instructor, in this a graduate teaching assistant (TA), in which the groups compared and discussed their results with the peers. The synthesized gold nanoparticles were saved for use in the second experiment.

Module #2—Extraction, Identification, and Quantification of Organophosphorous (OP) Pesticide Residues from Vegetables

Two “big questions” guided the design of this module: How are pesticides an issue in modern society? Can gold nanoparticles be used to identify and/or quantify the levels of pesticide residues in food and the environment? Students were shown a video clip from the 2012 *abc News* on “contamination of orange juice with pesticides” (<http://abcnews.go.com/US/orange-juice-safe-fda-carbendazim-safety-concern/story?id=15504105#.UYLSdkocPyU>) and encouraged to discuss the pros and cons of pesticide use in modern society, as well as reflect on their role as future chemical analysts. They discussed about the safety of vegetables and other food items sold in grocery stores. In groups of four, they were assigned a cabbage leaf spotted with unknown Organophosphorus (OP) pesticide (labeled A or B) and placed in an Erlenmeyer flask. They were also supplied with other relevant materials for the experiment.

Students devised an extraction procedure for the unknown pesticide in the assigned cabbage leaf. Each group shared their ideas with the rest of the class while stating the rationale for their methods. The groups were also encouraged to critique each other’s method as the TA guided them in reaching a consensus method. Upon extraction of the OP pesticides, students were encouraged to discuss how they could identify the unknown pesticides using gold nanoparticles, as well as describe other analytical techniques they could use to quantify the unknown pesticide residues from their cabbage leaf. They revisited the previously determined molar absorptivity of gold nanoparticles in which they discussed the advantage of high molar absorptivity for detection purposes.

The TA guided them in a productive discussion while refraining from giving direct answers.

In using gold nanoparticles for OP pesticide detection, students titrated their OP pesticide extract with small amounts (in microliters) of gold nanoparticles solution saved from module #1 while carrying out the UV-Visible studies following each titration—until a color change (from wine red to deep purple) was observed. They learned the optical and size-dependent properties of gold nanoparticles and their use as sensors for OP pesticides. The two unknown OP pesticides are distinguishable in that A (Fenthion) reacts faster with small amount of gold nanoparticles (80 microliters), with a red shift observed above 530 nm (532-534 nm) upon addition of 40 microliters of fenthion extract and a new peak forming with 80 microliters total. The second unknown OP pesticide B (Malathion) takes more gold nanoparticles to show a red shift at 530 nm with (1020 microliters)—no new peak formation. Finally, students quantified the amount of the OP pesticide from the cabbage leaves using the gas chromatography technique in which they calculated the area under the peak of their GC Chromatographs. They also discussed their findings as well as the possible identity of their unknown OP pesticide. In writing the laboratory reports, students were encouraged to search for published articles on nanotechnology for background information, as well as for supporting evidence of their claims on the findings.

Each module was accompanied by a guide for the instructor. The guides contain prompts that the instructor used to elicit students' reasoning and critical thinking on the experimental design, the role of the reagents, predictable results, observations, data analysis and interpretations, and conclusions. Prior to teaching these modules, the TA

was familiarized with the teaching approach (i.e., inquiry-based teaching), as well as the content of the modules by the two course developers.

Participants. Participants for this study were students enrolled in the quantitative analysis laboratory course (CHEM 2260) at the university in question. Typically, about 20-24 students are enrolled in the CHEM 2260 laboratory course each semester. A total of 61 students participated in this study. However, only 56 participants completed pre- and mid-survey instruments, and 55 completed mid- and post-survey instruments. Furthermore, eighteen (18) volunteer participants were recruited for the end-of-semester follow-up interviews. More information about the participants' demographic information is presented in the results section in Chapter 4.

Data Collection and Procedures

Data were collected in three semesters through multiple methods such as classroom observations, survey instruments, and open-ended semi-structured interviews. Triangulation of methods is important in securing the validity (inferential quality) of the findings (Creswell, 2007; Creswell & Plano Clark, 2007; Tashakkori & Teddlie, 1998). Descriptions of the structure and implementation of these methods with respect to this study are presented in the sub-sections below.

Classroom observations. In each semester, the researcher attended the lesson sessions for the two Nanoscale science modules in which observation field-notes were recorded. The observations were focused on the instructional approach of the lesson, class discussions, and execution of the experiment. A video camera and a voice recorder were also used to record the lesson sessions. Two groups (8 students) were randomly

selected for videotaping and recording of their discussions. These approaches (classroom field–notes, videotaping, and voice recording) are crucial in evaluating the fidelity of the implementations of the inquiry-based learning approach incorporated in these two modules. Tashakkori and Teddlie (1998) argue that persistent observation in collection of qualitative data is important in ensuring the quality of information, as well as trustworthiness of qualitative findings. They succinctly said:

Persistent observation is to provide “depth” for researchers by helping them identify the characteristics or aspects of the social scene that are most relevant to the particular question being pursued. This activity might also be more relevant to the quality of information than the quality of inferences/conclusions. (p. 90)

Survey instruments. Three survey instruments (two perceptions and attitudinal survey instruments, and an inquiry-based learning environment survey) were employed in the collection of quantitative data. The survey instruments included: chemistry attitudes and experiences questionnaire (CAEQ) (Dalgety, Coll, & Jones, 2003), Attitudinal Survey (Lewis & Seymour, 2004), and an evaluation survey for Enquiry-Based Learning (EBL) (Moore, 2006). The instruments were administered during the laboratory sessions as part of the normal classroom practice; meaning that all students were required to complete the surveys. Detailed descriptions of these instruments are discussed below.

Chemistry attitudes and experiences questionnaire (CAEQ)—Survey # 1. This instrument (referred in the current study as Survey # 1) was developed by Dalgety et al. (2003). It measures students’ perceptions and attitude toward science, particularly chemistry, confidence in undertaking chemistry tasks, and learning experiences. The instrument was piloted with first-year university chemistry students (n = 129) from a

chemistry course in New Zealand. Moreover, it was re-tested with first-year university chemistry students from two institutions at the beginning of the academic year ($n = 332$) and the end of the semester ($n = 337$) (Dalgety et al., 2003) to secure reliability and validity. Prior to testing the instrument the items were examined by a panel of experts in chemistry to secure content validity. It was then administered to 19 participants who were also interviewed to check for readability and comprehension of the items. The re-testing (round 2) of the instrument was geared towards securing construct validity, predictive validity, and concurrent validity (Dalgety et al., 2003). According to Tashakkori and Teddlie (1998), construct validity is the degree to which the instrument measures the construct; predictive validity examines if the instrument can predict a specific outcome; and concurrent validity checks if the measure obtained from the instrument correlates well with an already validated measure of the same construct. For concurrent validity, obtained test scores should exhibit a high correlation with the established test scores (Tashakkori & Teddlie, 1998).

According to Dalgety et al., the validated CAEQ instrument contains a total of 21 items (semantic differential scale: 1 to 7) under the category “*attitude-toward-chemistry and science*” with five sub-categories: attitude toward chemists, skills of chemists, attitude toward chemistry in society, leisure interest in chemistry, and career interest in chemistry. The “*confidence category*” consists of 17 Likert-scale items (“Totally Confident” to “Not Confident”), while the “*learning experiences category*” comprises of 31 Likert-scale items (Strongly Agree to Strongly Disagree), with four sub-categories: demonstrator learning experiences, laboratory class learning experiences, lecture learning experiences and tutorial learning experiences.

In the current study, 19 items from the attitude toward chemistry and science category, and 15 items from the confidence category were selected from Dalgety et al.'s work. Two more items were added—one in each of these two categories. The items were selected based on the perceived relevance to the current study. Two expert researchers reviewed all the items and reached a consensus on the items to select (face validity).

An additional section regarding student demographic information was included in this instrument in which each student was given a pseudonymous identification number (M01, M02, M03..., etc.) as well as asked to provide information about the following: gender; current GPA; hours of study per week; years of chemistry including high school and university; and major. This instrument was administered three times in each semester of data collection, that is, at the beginning (pre-survey); after students cover most of the conventional laboratory experiments (mid-survey); and after completing the nanotechnology-chemistry experiments (post-survey). A sample of the instrument is presented in Appendix A; Survey Instruments—Chemistry Attitudes and Perceptions Survey #1.

Enquiry-based learning (EBL) survey—Survey #2. This instrument was developed to evaluate students' perceptions and attitudes towards an inquiry-based learning environment (Moore, 2006). It comprises of 41 structured items that follow a 5-point Likert-Scale (1= strongly disagree and 5 = strongly agree). It was administered two times during each semester of data collection—as mid-and post-surveys, or prior to and after the intervention experiments. At this time, it was assumed that students had gained substantial experience with the laboratory experiments. A sample of the instrument is

presented in Appendix A; Survey Instruments—Enquiry-Based Learning Environment Survey #2.

Attitudinal survey—Survey # 3. According to Lewis and Seymour (2004), this instrument measures student perceptions of their classroom experience such as perceptions towards the course, the discipline, and their own learning. The author's instrument contains a total of 21 items. Specific categories include perceptions about: laboratory experiences, learning strategies— "*I learn well by...* ", and strategies for conceptual understanding— "*I know I understand when...* " The items follow a 7-point scale (strongly disagree = 1 to don't know = 7). Sixteen (16) out of 21 items were adopted in the current study. Moreover, a 5-point scale was used (strongly disagree = 1 to strongly agree = 5); rather than the 7-point scale (e.g., see Appendix A; Survey Instruments—Perceptions and Attitudinal Survey #3). Like EBL survey instrument, this instrument was administered two times during the semester—mid- and post-survey.

During the mid-and-post survey completion, the three survey instruments were administered to students as one document, but with the three instruments merged and explicitly labeled (i.e., survey # 1, # 2, #3). Additional open-ended items were also added to the packet of the three survey instruments to assess students' perceptions about the experiments. These items elicited students to reflect on their laboratory experiences and provide their responses to each item. Students were required to provide indicate which experiment they learned the most, the least, and was most relevant to their daily-experiences and modern society. They were also supposed to provide reasons for the choice of experiments based on each of the aforementioned parts. The duration for completing the three surveys was about 20 min.

Interviews. Six volunteer participants were selected for interviews in each semester of data collection. A total of 18 interviewees participated in the interviews. Priority was given to participants who had completed the three survey instruments discussed above. Individual interviews were conducted with each participant at the end of the semester, for the three semesters of data collection. The interview protocol consisted of two parts—general laboratory experiences and/or perceptions (*Part 1*), and reflection on the survey responses (*Part 2*)—see Appendix B. Part 1 of the interview was considered important in eliciting students’ perceptions and/or experiences about the quantitative analysis laboratory course, while part 2 helped the researcher in elucidating the factors that led to students’ change of perceptions and attitude towards chemistry/science, or the course in question.

During Part 1 of the interview, the participants were asked to describe: (1) their general experiences about the quantitative analysis laboratory course (CHEM 2260) they took; (2) their general view about the normal laboratory experiments (the non-nanotechnology) that they were exposed to in this course—what they liked and did not like about these experiments; (3) their experiences with the nanotechnology units—what they liked and did not like about these experiments; (4) the method instruction they perceived useful in helping them learn concepts better; their experiences in using inquiry-based learning approach (prompt); and (5) the changes, if any, they would make on the course if they were the instructor of record for CHEM 2260 course in the subsequent semester.

Prior to the interviews, the researcher identified the key items from mid-and post surveys (quantitative data) in which the participants showed both positive and negative

changes in attitude and/or perceptions, The identified items were used in Part 2 of the interview. During Part 2 of the interview, participants were asked to explain the reasons for their change of scores on the identified items. Further probing was employed, when necessary, to gather detailed information about the factors the participants highlighted. The entire interview (Parts 1 and 2) lasted between 20 and 45 minutes with each participant. Each participant was compensated a \$15 gift card for their time. All the interviews were audio recorded using a voice recorder and a camera.

Data Analysis Procedures

Sequential data analysis was employed, in which the analysis of the quantitative data preceded the qualitative data (Creswell & Plano Clark, 2007). Overall, the analysis followed the steps outlined in the Follow-up Explanations Model previously discussed. A discussion of how each data (i.e., quantitative and qualitative) was analyzed in the current study is presented below.

Quantitative data. The quantitative data collected from the survey instruments was analyzed separately from the qualitative data. The analysis followed immediately after the completion of the three instruments, at the end of the semester. Analyzing quantitative data prior to qualitative was crucial in identifying the items and cases (participants) to be selected for the follow-up interviews (Creswell & Plano Clark, 2007). Prior to the analysis, negative statements (items) from the surveys were identified and converted to positive statements. The corresponding scores were also adjusted accordingly. This step was important in establishing the sample mean scores (i.e., the

average attitudinal/perception score on Pre-, Mid-, and Post-surveys) as well as the mean scores for individual items.

Furthermore, adjustments were made to relevant survey instruments to ensure uniformity in which the least numerical value for each scale was associated with strong negative attitude/perception, median value (Likert-scale = 3; Semantic differential scale = 4) was associated with a neutral attitude/perception, and the highest value of the scale with the strong positive attitude/perception. That is, for semantic differential scaled items, 1 = strong negative attitude/perception and 7 = strong positive attitude/perception; and for Likert- scaled items, 1 = strong negative and 5 = strong positive attitude/perception.

Structured survey responses. Statistical Package for the Social Sciences (SPSS), quantitative analysis software, was used in the analysis of participants' survey responses (scores). Initial analysis followed comparisons between the pre and mid, and the mid and post surveys scores, based on each structured item as well as the group pre, mid, and post scores. Items that displayed statistically significant, and/or non-significant results contrary to the expectations of the researcher were followed- up with interviews (second phase) to ascertain reasons for such observations (Creswell & Plano Clark, 2007). More emphasis was placed on the difference in scores between the mid and post surveys—before and after the intervention units, respectively. This comparison was considered important for identifying specific factors that led to students' change of perceptions following exposure to the course experiments.

Parametric statistics was considered in the analysis of quantitative data in this study. This follows from the assumptions that the data from this study are normally distributed, and have equal variance (homogeneity of variance) (Hinkle, Wiersma, &

Jurs, 1998; StatSoft, (2013)). According to the central limit theorem, quantitative data are assumed to be normally distributed if the sample size ($n = 30$) (Hinkle et al., 1998; StatSoft, (2013)). In the current study, the sample size ($n = 55$) exceeds the aforementioned size, hence normality was assumed. Levene's test was employed to test the homogeneity of variance assumption. The resulting p-values from the Levene's test, based on individual items, were greater than 0.05, hence the assumption of equal variance was met.

Paired sample t-test method (Hinkle et al., 1998; StatSoft, (2013)) was employed to compute the difference in mean scores between pre and mid-surveys, and mid and post-surveys for each structured item at 95% confidence interval (i.e., $\alpha = 0.05$). In the current study, the mean values below 3 and 4 for the Likert-scaled and semantic differential scaled items, respectively, are associated with negative attitude/perceptions. The mean values > 3 (Likert-scaled items) and > 4 (semantic differential scaled items) are associated with positive attitude/perceptions, whereas the mean values equal to 3 and 4 for the Likert-scaled and semantic differential scaled items, respectively, are associated with neutral attitude/perceptions. The items with p-values ≤ 0.05 are considered statistically significant (Hinkle et al., 1998). The information gathered from this analysis is vital in ascertaining the influence (positive, neutral, or negative), if any, of the intervention units on students' attitudes/perceptions.

Furthermore, information obtained about the means is useful in making inferences from the sample to the population (StatSoft, (2013)). Frequency statistics was also employed to make summaries about the sample in question as well as the collected data.

Additionally, independent sample t-test was used to compare attitude/perceptions mean scores between female and male participants (Hinkle et al., 1998; StatSoft, (2013)).

Demographic information were grouped into categories, which were then correlated with attitudinal/perception mean scores (based on pre and mid, and mid and post) to determine significant differences between the group means—through one-way analysis of variance (ANOVA) (Hinkle et al., 1998). The groups correlated with the attitudinal/perception mean scores in this study are presented below:

- 1) GPA: < 2.29, 3-3.5, 3.60-3.3.89, ≥ 3.90 ;
- 2) Major: Chemistry, Biochemistry, Other sciences (biology, physics, secondary education/chemistry, and engineering);
- 3) Years of study of chemistry: 1-2, 3-4, 5-6, ≥ 7 ;
- 4) Hours of study per week: 1-5.9, 6-10.9, 11-15.9, 16-24.9, ≥ 25 ; and
- 5) Class level: Freshmen, Sophomore, Junior, and Senior levels.

Tukey's test will be employed to determine which group mean(s) is or are statistically significant at alpha (α) = 0.05 (Hinkle et al., 1998; StatSoft, (2013)).

Open-ended survey responses—part 1 of the survey items. Participants' responses from the open-ended survey items were analyzed separately from the structured responses. Prior to the analysis, the responses from the first part of each item were read and re-read to identify the experiments stated by the participants. The identified experiments were then put into categories (e.g., Nanoscale science experiment # 1, 2; titration of calcium and zinc, gravimetric determination of sulfate, etc.). The categories were entered in an Access Microsoft Office file for analysis with SPSS software.

Frequency analysis was employed to determine the percent of participants associated with each category (percent frequency). The analysis of responses regarding part 2 of the open-ended survey items is discussed under the qualitative data section below.

Qualitative data. Data from the classroom observation field notes, open-ended survey items (part 2 of the survey items), and interviews were typed and/or transcribed in separate word documents. Responses addressing each item, particularly for part 2 of the open-ended survey items were merged together; however, student ID numbers were retained for reporting of the findings. The word documents were then converted into notepads for analysis with HyperResearch qualitative analysis software (<http://www.researchware.com>). HyperResearch software helps in the organization of codes and development of codes into categories. Data from each of the aforementioned sources were analyzed separately.

Open-ended survey responses—part 2 of the survey items. This data were analyzed by the researcher and another qualitative expert who has experience with HyperResearch software. The two individuals independently coded the data and compared the identified codes. Differences in codes were discussed and conflict resolved until an inter-coder reliability of 90% was reached. The two individuals developed the codes into major categories, which were then merged with the qualitative data obtained from the interviews and observation field-notes to generate themes (Creswell, 2007).

Interview data—part 1 & 2 of the interview. The researcher read and re-read the data to ensure it is clean from typos. Next, the researcher and another expert in qualitative research independently read and re-read the transcripts to make sense of the data (Creswell, 2007). The analysis were informed by the interview questions (part 1 of the

interview) and identified survey items (part 2 of the interview), as well as the main research questions guiding the study (Creswell, 2007). For each data set (part 1 and part 2 of the interview), the two individuals independently coded 5 interview transcripts using HyperResearch software, compared the coding scheme. Differences, if any, in codes were discussed and the discrepancies resolved until inter-coder reliability > 80% was reached. The two individuals together developed the identified codes from each data source into categories.

The remaining interview transcripts (for both parts of the interview) were analyzed by the researcher in which the previously identified categories were applied in the relevant sections of the transcripts while allowing for new codes to emerge. Codes from each data source were then separately developed into major categories. In particular, major categories generated from interview part 1 were merged with related categories from other data sources to generate themes—more information about this process is provided in data triangulation sub-section. Related major categories from interview part 2 were merged to form themes and/or sub-themes. The latter was used in the interpretation of quantitative data of interest, that is, the previously identified survey responses.

Classroom observation field-notes/video tape/voice recording. The analysis of field-notes was done by the two individuals previously mentioned. The individuals independently coded the field-notes gathered from the Nanoscale science units. Patterns related to the participants' experiences or perceptions about the unit were identified and developed into categories. The categories were compared and any differences resolved until a consensus was reached (i.e., > 80% inter-coder reliability). Moreover, the field-notes were analyzed in conjunction with the classroom video clips and voice recorded

data to ascertain the fidelity of the inquiry-based learning approach implemented in the two Nanoscale science units.

Triangulation of qualitative data. The researcher merged related major categories identified from different data sources (i.e., observation field-notes, interview part 1, and part 2 of the open-ended survey responses) to generate themes. Unrelated major categories that appeared to be useful in the interpretation of the quantitative data and/or qualitative data were treated as sub-themes. The identified themes and sub-themes were then cross verified against the data (confirmability audit) by a third party to ensure internal validity of the interpretations (Tashakkori & Teddlie, 1998). According to Tashakkori and Teddlie, confirmability audit (A.K.A “inferential consistency audit”) involves “attesting that the findings and interpretations are supported by the data and are internally coherent” (p. 93). Finally, the generated themes were used to address the research questions.

Securing Validity and Reliability of the Survey Instruments

The validity of the survey instruments to be used in the collection of data in this study were tested and re-tested by the developers for face validity, content validity, concurrent validity, predictive validity, and construct validity (Tashakkori & Teddlie, 1998). The instruments have also been used in some past studies related to attitudes and perceptions (Dalgety et al., 2003; Lucas & Rowley, 2011; Pringle & Henderleiter, 1999). Although face validity has been secured in the selection of the relevant survey items for the current study, the researcher assumes that the instruments meet the other validity measures.

Tashakkori and Teddlie (1998) define reliability as “the degree to which the results of a measurement accurately represent the true “magnitude” or “quality” of a construct” (p. 82). SPSS was used to verify the internal consistency (a type of reliability) of the instruments based on the fall 2012 and spring 2013 quantitative data. According to Tashakkori and Teddlie (1998), internal consistency of the instrument involves correlating test scores between items. Evaluation of internal consistency of the instrument can be achieved by determining Cronbach’s coefficient alpha (Hinkle et al., 1998; StatSoft, (2013); Tashakkori & Teddlie, 1998). If the obtained Cronbach’s coefficient is > 0.7 , the instrument is considered to exhibit internal reliability (Hinkle et al., 1998). Based on the two semester data, the determined Cronbach’s coefficients alpha for the three questionnaires were found to be reliable: Questionnaire #1, CAEQ—0.91; Questionnaire #2, EBL Survey—0.96, and Questionnaire #3, Attitudinal Survey—0.81. A summary of the Cronbach’s coefficients for these surveys is presented in Table 3.2.

Chapter Summary

In this chapter, I have presented the research design, and research contexts, where I have described the course in which the two Nanoscale science modules in questions were implemented, the structure and content of the Nanoscale science modules, and the participants involved in the current study. I have also discussed how data were collected and analyzed to answer the main research questions. In particular, detailed descriptions of three data sources: three survey instruments (quantitative data collection methods), and classroom observations and end-of-semester in-depth-interviews (qualitative data collection methods) have been presented. Finally, I have discussed how the reliability of

the instruments was achieved, as well as the reliability coefficients obtained. The next chapter, Chapter 4, is the presentation and discussion of findings based on the analyzed data.

Table 3.1 A Summary of Reliability Coefficients of the Survey Instruments

Questionnaire #1: CAEQ		
Reliability Statistics		
Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
.903	.910	36
Questionnaire #2: EBL Survey		
Reliability Statistics		
Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
.959	.960	41
Questionnaire #3: Attitudinal Survey		
Reliability Statistics		
Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
.805	.810	16

CHAPTER 4 : RESULTS

Results on Student Demographic Information

Analysis of students' demographic information showed that out of 55 students who completed the three surveys, twenty two (40%) were chemistry majors, sixteen (29%) biochemistry majors, and seventeen (~31%) were from other majors (i.e., Biology = 4; Biomedical Sciences = 2; Physics = 2; Chemical Engineering = 2; Dietetics = 1; Food marketing = 1; Geochemistry = 1; Geology = 1; German = 1; Math: Secondary Education = 1; and Guest student undergraduate = 1). Figure 4.1 shows a summary of the results based on student major.

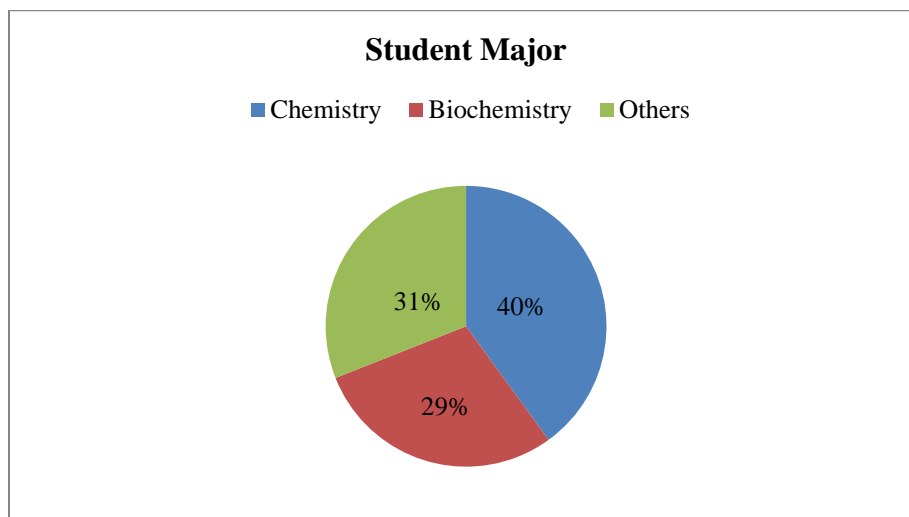


Figure 4.1 A Summary of Frequency Results Based on Student Major

Analysis by class level revealed that three (6%) were Freshmen, five (9%) Sophomore, twenty one (38%) Junior, and were twenty six (47%) Senior—see Figure 4.2 (a). Results on analysis by GPA indicated that 8 participants (~15%) had a GPA < 2.99; eighteen (~33%) had a GPA between 3 and 3.5; sixteen (29%) had a GPA between 3.65 and 3.89, and eight (~16%) had a GPA ≥ 3.95 —see Figure 4.2 (b). Five participants did not provide information about their GPAs.

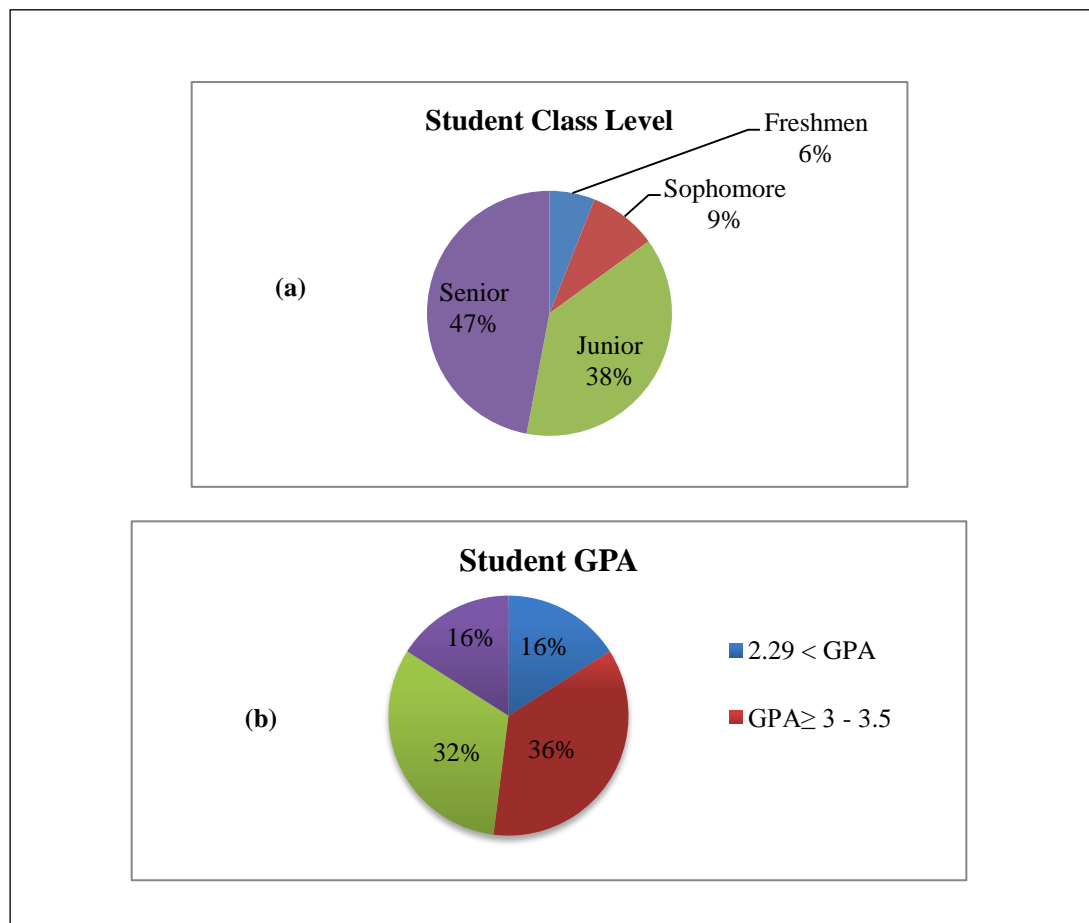


Figure 4.2 A Summary of Frequency Results Based on Class Level (a) and GPA (b)

Frequency analysis of the data by hours of study per week indicated a range of 1 hour to 80 hours (hrs). In particular, eight (~15%) participants were in the category of 1-5.9 hrs of study, twelve (~23%) were in the category of 6-10 hrs, eleven (21%) fell in 11-15 hrs category, ten (19%) were in the category of 16-24 hrs, and twelve (~23%) expressed 6-10 hrs of study (see Figure 4.3 (a)). Two participants did not provide information about their hours of study.

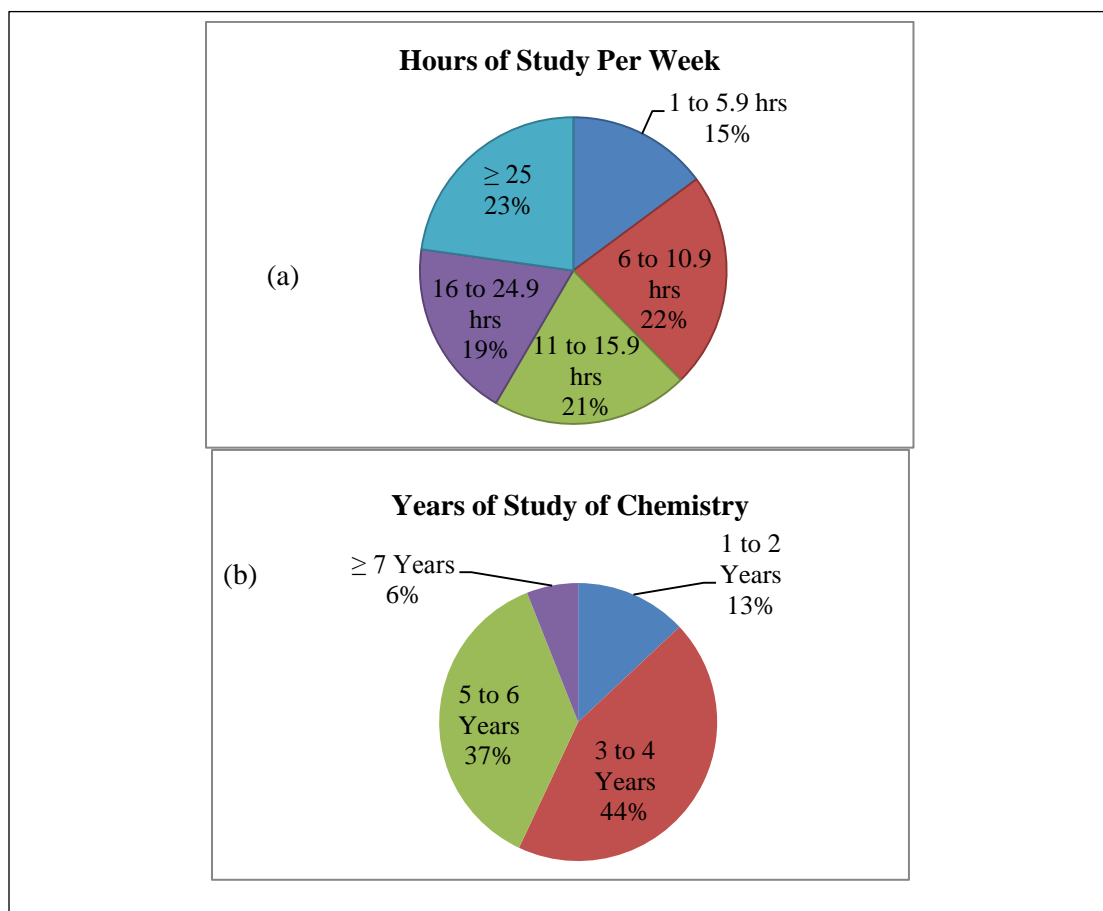


Figure 4.3 A Summary of Frequency Results Based on Hours of Study Per Week (a) and Years of Chemistry (b)

Finally, frequency analysis based on the Years of chemistry, including college level indicate that 7 participants (~13%) had between 1-3 years of chemistry, twenty four (~44%) had 3 to 4 years, twenty (37%) had between 5 and 6, and three (~6%) had 7 to 9 years. A summary of the results is shown in Figure 4.3 (b). One participant did not provide information on this category.

Structured Survey Responses—Quantitative Data

Findings reported herein are based on the participants who completed the pre/mid (N = 56) and mid/post (N = 55) survey instruments. Analysis of the survey scores yielded four main themes and sub-themes based on the survey items. The main themes include: (1) students' perceptions about chemistry, (2) confidence undertaking experimental tasks, (3) students' perceptions about inquiry-based environment, and (4) students' perceptions towards the course, the discipline, and their own learning.

Theme 1: Students' Perceptions about Chemistry

Paired T-test of pre/mid and mid/post indicated no statistical differences in the mean scores on perceptions about chemistry at 95% confidence interval. Figure 4.4 shows a summary of the mean score comparisons between pre/mid and mid/post based on students' perceptions about chemistry. A comparison between the pre/mid mean scores shows a decrease in the perceptions mean score following exposure to the conventional experiments (Mean: Pre = 5.37; Mid = 5.26, $\Delta\text{Mean} = -0.10$, $p = 0.112$; $N = 56$). However, a comparison between the mid/post mean scores indicated a slight increase in the mean post score (Mean: Mid = 5.27; Post = 5.31, $\Delta\text{Mean} = 0.04$, $p = 0.420$; $N = 55$).

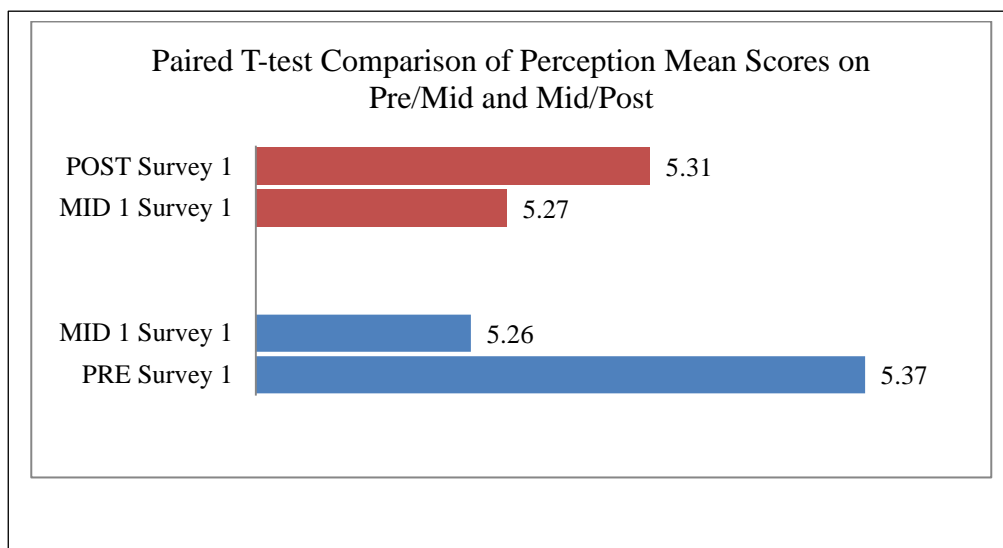


Figure 4.4 A Summary of Pre/Mid and Mid/Post Mean Comparison on Students' Perceptions about Chemistry

A comparison of mean scores between pre and mid based on individual survey #1 items revealed statistically significant differences in 3 out of 20 perception items (e.g., see Table 4.1). Following the exposure to the conventional experiments (mid-survey), the students felt that:

1. *Science documentaries were less enjoyable* (Pre = 5.50, Mid = 5.11, $\Delta\text{Mean} = -0.393$; $p = 0.030$);
2. *Chemistry jobs were less interesting* (Pre = 5.64, Mid = 5.30, $\Delta\text{Mean} = -0.339$; $p = 0.043$); and
3. *Chemistry jobs were less exciting* (Pre = 5.04, Mid = 4.57, $\Delta\text{Mean} = -0.464$; $p = 0.018$).

Paired t-test analysis on the mid and post mean scores of individual survey #1 items revealed a statistically significant improvement on students' perceptions about the

flexibility of chemists' ideas, and chemistry websites—Table 4.1. In the post survey (following the Nanoscale science experiments), students felt that “*chemists are more flexible in the ideas*” (Mid = 4.74, Post = 5.24, $\Delta\text{Mean} = 0.50$; $p = 0.006$), and “*Chemistry websites are more interesting*” (Mid = 4.64, Post = 5.15, $\Delta\text{Mean} = 0.51$; $p = 0.003$).

Overall, the participants' expressed positive perceptions (i.e., mean score > 4) about chemists, chemistry research, science documentaries, chemistry websites, and chemistry jobs based on the pre, mid, and post survey # 1 mean scores. However, on the category of “chemistry jobs”, they had negative perceptions (i.e., Mean score < 4) —they expressed that “*chemistry jobs are challenging*” (Mean: Pre = 2.38, $N = 56$; Mid = 2.55, Post = 2.47, $N = 55$).

An independent t-test analysis on the influence of gender on participants' perceptions about chemistry revealed that male participants had a slightly higher perception mean score than the female participants based on the pre, mid and post group mean scores:

- 1) Pre {Mean: Male ($n = 34$) = 5.44, Female ($n = 23$) = 5.27, $\Delta\text{Mean} = 0.16$, $p = 0.336$ },
- 2) Mid {Mean: Male ($n = 35$) = 5.30, Female ($n = 22$) = 5.21, $\Delta\text{Mean} = 0.09$, $p = 0.647$ }, and
- 3) Post {Mean: Male ($n = 33$) = 5.38, Female ($n = 23$) = 5.21, $\Delta\text{Mean} = 0.16$, $p = 0.450$ }.

Both groups had the highest perception mean score at the beginning of the course.

Independent t-test analyses of individual items indicated statistically significant mean differences between the male and female participants on 2 of the 20 items. Such

Table 4.1 Pre/Mid and Mid/Post Paired Sample T-test Results on Students' Perceptions about Chemistry

Variable/Survey Item	Matched Pair Pre/Mid Mean Score (<i>N</i> = 56)		Mean Difference	P- value	Matched Pair Mid/Post (<i>N</i> = 55)		Mean Difference	P- value
Chemists are socially aware.	Mid	5.27	0.34	0.131	Post	5.49	0.218	0.204
	Pre	4.93			Mid	5.27		
Chemists are environmentally aware.	Mid	5.82	0.04	0.873	Post	5.55	-0.291	0.254
	Pre	5.79			Mid	5.84		
Chemists are fixed in their ideas.	Mid	4.57	-0.07	0.742	Post	5.24	0.500	0.006*
	Pre	4.82			Mid	4.74		
Chemists care about the effects of their results.	Mid	5.15	-0.26	0.260	Post	5.19	-0.019	0.936
	Pre	5.40			Mid	5.20		
Chemists are imaginative.	Mid	5.62	-0.02	0.921	Post	5.64	0.018	0.921
	Pre	5.64			Mid	5.62		
Chemists are friendly.	Mid	5.20	0.07	0.584	Post	5.02	-0.200	0.213
	Pre	5.13			Mid	5.22		
Chemists are inquisitive.	Mid	5.53	-0.26	0.159	Post	5.66	0.132	0.442
	Pre	5.78			Mid	5.53		
Chemists are patient.	Mid	5.45	0.13	0.504	Post	5.38	-0.057	0.745
	Pre	5.33			Mid	5.43		
Chemistry research helps people.	Mid	6.13	-0.13	0.424	Post	6.07	-0.018	0.864
	Pre	6.25			Mid	6.09		
Chemistry research increases the quality of life.	Mid	6.16	-0.04	0.799	Post	5.84	-0.291	0.070
	Pre	6.20			Mid	6.13		
Chemistry research solves problems.	Mid	5.68	-0.18	0.279	Post	5.71	0.036	0.788
	Pre	5.86			Mid	5.67		
Chemistry research advances society.	Mid	6.11	-0.04	0.827	Post	5.87	-0.236	0.194
	Pre	6.14			Mid	6.11		

(*) Indicates the mean difference statistically significant at 95% confidence level

Table 4.1— Continued

Science documentaries are enjoyable.	Mid	5.11	-0.39	0.030*	Post	5.24	0.164	0.303
	Pre	5.50			Mid	5.07		
Science documentaries are informative.	Mid	6.21	-0.04	0.766	Post	6.15	-0.073	0.485
	Pre	6.25			Mid	6.22		
Chemistry websites are interesting.	Mid	4.63	-0.36	0.091	Post	5.15	0.509	0.003*
	Pre	4.98			Mid	4.64		
Chemistry jobs are challenging.	Mid	2.52	0.14	0.419	Post	2.47	-0.073	0.642
	Pre	2.38			Mid	2.55		
Chemistry jobs are varied.	Mid	4.82	0.09	0.654	Post	4.69	-0.109	0.579
	Pre	4.73			Mid	4.80		
Chemistry jobs are interesting.	Mid	5.30	-0.34	0.043*	Post	5.49	0.182	0.267
	Pre	5.64			Mid	5.31		
Chemistry jobs are satisfying.	Mid	5.32	-0.18	0.322	Post	5.38	0.036	0.839
	Pre	5.50			Mid	5.35		
Chemistry jobs are exciting.	Mid	4.57	-0.46	0.018*	Post	4.95	0.364	0.091
	Pre	5.04			Mid	4.58		

(*) Indicates the mean difference statistically significant at 95% confidence level

differences were noted on the category of “chemistry research” and “science documentaries”. In particular, males strongly felt that chemistry research improves the quality of life compared to females. Additionally, males indicated that science documentaries are more enjoyable than women did. Results of these two items are presented below:

- a) *Chemistry research improves the quality of life* (Pre: Male = 6.44, Female = 5.83, $\Delta\text{Mean} = 0.615$, $p = 0.020$), and
- b) *Science documentaries are enjoyable* (Pre: Male = 5.79, Female = 5.00, $\Delta\text{Mean} = 0.794$, $p = 0.045$; Mid: Male = 5.51, Female = 4.50, $\Delta\text{Mean} = 1.014$, $p = 0.042$).

Findings on ANOVA analysis based on groups indicated that GPA, Major, Hours of study per week, and Years of study of chemistry had no significant influence on students’ perception about chemistry based on the pre, mid, and post scores (survey #1). In contrast, class level had a significant influence on students’ perceptions (at 95% confidence level) based on pre and post scores. A summary of the ANOVA results is shown on Table 4.2. The F-test and p-values based on demographic groups are presented below:

1. *GPA* (Pre: $F = 1.835$, $p = 0.153$; Mid: $F = 0.906$, $p = 0.445$; Post: $F = 2.383$, $p = 0.081$);
2. *Major* (Pre: $F = 0.178$, $p = 0.837$; Mid: $F = 0.574$, $p = 0.567$; Post: $F = 0.246$, $p = 0.782$);
3. *Hours of study of per week* (Pre: $F = 0.338$, $p = 0.851$; Mid: $F = 0.259$, $p = 0.903$; Post: $F = 0.207$, $p = 0.933$);

4. *Years of study of chemistry* (Pre: $F = 0.259$, $p = 0.854$; Mid: $F = 0.551$, $p = 0.650$; Post: $F = 0.497$, $p = 0.686$); and
5. *Class level* (Pre: $F = 3.189$, $p = 0.031$; Mid: $F = 2.624$, $p = 0.060$; Post: $F = 3.337$, $p = 0.026$).

Tukey's test on Class level revealed significant mean differences between Freshmen students (1st year) and the Seniors (finalists) on their perceptions about chemistry, based on pre- ($\Delta\text{Mean} = 0.952$, $p = 0.048$) and post- ($\Delta\text{Mean} = 1.289$, $p = 0.032$) survey # 1 perception scores. ANOVA analysis on individual items based on pre scores revealed significant mean differences between the Freshmen and Seniors ($\Delta\text{Mean} = 1.923$, $p = 0.016$), and Sophomore and Seniors ($\Delta\text{Mean} = 1.523$, $p = 0.017$) on the item "*chemistry jobs are satisfying*" ($F = 2.897$, $p = 0.044$) —Freshmen and Sophomores had more positive perceptions on this item than Seniors. Furthermore, significant mean differences based on post survey were noted between groups on three items:

- a. "*Chemistry websites are interesting*" ($F = 3.723$, $p = 0.017$); Freshmen and Seniors ($\Delta\text{Mean} = 2.462$, $p = 0.024$) —Freshmen had more positive perceptions than Seniors.
- b. "*Chemistry jobs are interesting*" ($F = 4.524$, $P = 0.007$); Freshmen and Seniors ($\Delta\text{Mean} = 1.734$, $p = 0.039$), as well as Juniors and Seniors ($\Delta\text{Mean} = 0.941$, $p = 0.015$) —Freshmen and Juniors had more positive perceptions than Seniors.
- c. "*Chemistry jobs are satisfying*" ($F = 4.524$, $p = 0.007$); Freshmen and Seniors ($\Delta\text{Mean} = 2.000$, $p = 0.024$) —Freshmen had more positive perceptions than Seniors.

Table 4.2 Anova Results on Class Level and Perceptions about Chemistry

		Sum of Squares	df	Mean Square	F	Sig.(P-Value)
Perceptions PRE Survey # 1	Between Groups	3.265	3	1.088	3.189	.031*
	Within Groups	18.086	53	.341		
	Total	21.351	56			
Perceptions MID Survey # 1	Between Groups	3.933	3	1.311	2.624	.060
	Within Groups	26.483	53	.500		
	Total	30.416	56			
Perceptions POST Survey # 1	Between Groups	5.581	3	1.860	3.337	.026*
	Within Groups	28.988	52	.557		
	Total	34.569	55			
Confidence PRE Survey # 1	Between Groups	1.989	3	.663	1.361	.265
	Within Groups	25.810	53	.487		
	Total	27.799	56			
Confidence MID Survey # 1	Between Groups	1.734	3	.578	.904	.445
	Within Groups	33.880	53	.639		
	Total	35.615	56			
Confidence POST Survey # 1	Between Groups	1.499	3	.500	1.251	.301
	Within Groups	20.778	52	.400		
	Total	22.277	55			

(*) Indicates statistically significant differences between groups at 95% confidence level

The calculated effect size (Cohen's d) (Hinkle et al., 1998) on mid/post survey # 1 mean scores was 0.11 (~ 0.1) — see calculations based on the equation below. This indicates a very small difference between the post and mid mean scores on students' perceptions about chemistry.

$$\text{Cohen's } d (\text{Effect Size}) = \frac{\bar{x}_1 - \bar{x}_2}{s};$$

where \bar{x}_1 is Post Mean score; \bar{x}_2 is Mid Mean score; and s is the standard deviation of the sample means. Based on the paired t-test results previously provided, Cohen's d was calculated as follows:

$$d = (5.307 - 5.271) / (0.3334) = \mathbf{0.108} (\sim \mathbf{0.1})$$

$$d = \sim \mathbf{0.1}$$

Theme 2: Students' Confidence in Undertaking Chemistry Experimental Tasks

A paired sample t-test comparison of mean scores between pre/mid and mid/post surveys indicated no significant improvement on students' confidence in undertaking experimental tasks over the semester, and based on all the items (i.e., Mean: Pre = 3.96; Mid = 3.94, $\Delta\text{Mean} = 0.02$, $N = 56$, $p = 0.798$; and Mid = 3.93; Post = 4.03, $\Delta\text{Mean} = 0.10$, $N = 55$, $p = 0.306$). However, analysis of individual items based on mid/post mean score comparison indicated a significant improvement on students' confidence towards "*Designing and conducting [a] chemistry experiment*" in the post-survey (Mid = 3.38, Post = 3.71, $\Delta\text{Mean} = 0.33$; $p = 0.007$).

A summary of the mean score comparisons between pre/mid and mid/post on confidence in undertaking chemistry experimental tasks is shown in Table 4.3. Overall, the post mean scores on "confidence in undertaking tasks" were slightly higher compared to the mid mean scores, except on "*Determining what the answer is required from a written description of a chemistry experiment*" (Mid = 3.98; post = 3.96, $\Delta\text{Mean} = -0.02$, $p = 0.883$) and "*Applying chemistry concepts learnt to real-world experiences*" (Mid = 3.96; post = 3.91, $\Delta\text{Mean} = -0.06$, $p = 0.705$).

Independent t-test analyses on the influence of gender on participants' confidence in undertaking experimental tasks revealed that male participants had slightly higher mean scores than the female participants based on the pre, mid and post scores. However, female participants showed increased confidence in carrying out experimental tasks compared to the male as the semester progressed:

1. Pre {Mean: Male (n = 34) = 4.01, Female (n = 23) = 3.79, Δ Mean = 0.22, p = 0.247},
2. Mid {Mean: Male (n = 35) = 4.02, Female (n = 22) = 3.87, Δ Mean = 0.15, p = 0.501}, and
3. Post {Mean: Male (n = 33) = 4.07, Female (n = 23) = 3.92, Δ Mean = 0.15, p = 0.379}.

An independent t-test analysis on individual items indicated statistically significant mean differences between male and female participants on their confidence in undertaking the following tasks:

- a) *Ensuring the data obtained from the experiment is accurate* (Pre: Male = 4.15, Female = 3.65, Δ Mean = 0.495, p = 0.031),
- b) *Proposing a meaningful question that can be answered experimentally* (Pre: Male = 4.00, Female = 3.43, Δ Mean = 0.565, p = 0.027),
- c) *Learning chemistry theory* (Pre: Male = 4.15, Female = 3.61, Δ Mean = 0.538, p = 0.033), and
- d) *Applying chemistry concepts learned to real-world experiences* (Post: Male = 4.09, Female = 3.61, Δ Mean = 0.482, p = 0.030).

Table 4.3 Pre-Mid and Mid-Post Paired Sample T-test Results on Students' Confidence in Undertaking Tasks

Variable/Survey Item	Matched Pair Pre/Mid Mean Score (N = 56)			P- value	Matched Pair Mid/Post (N = 55)		
			Mean Difference			Mean Difference	P- value
Reading the procedures for an experiment and conducting the experiment without supervision.	Mid	4.04	0.05	0.690	Post	4.09	0.371
	Pre	3.98			Mid	3.98	
Designing and conducting a chemistry experiment.	Mid	3.39	0.04	0.811	Post	3.71	0.007*
	Pre	3.36			Mid	3.38	
Tutoring another student in a second year chemistry course.	Mid	3.77	0.04	0.827	Post	3.91	0.162
	Pre	3.73			Mid	3.74	
Determining what the answer is required from a written description of a chemistry experiment.	Mid	3.98	0.04	0.805	Post	3.96	-0.02
	Pre	3.95			Mid	3.98	
Ensuring that data obtained from an experiment is accurate.	Mid	3.75	-0.20	0.078	Post	3.87	0.15
	Pre	3.95			Mid	3.73	
Proposing a meaningful question that could be answered experimentally.	Mid	3.86	0.05	0.713	Post	3.93	0.11
	Pre	3.80			Mid	3.81	
Explaining something that you learnt in this chemistry course to another person.	Mid	4.07	-0.04	0.811	Post	4.13	0.13
	Pre	4.11			Mid	4.00	
Know how to convert data obtained in a chemistry experiment into a result.	Mid	4.04	-0.04	0.805	Post	4.07	0.07
	Pre	4.07			Mid	4.00	

(*) Indicates the mean difference statistically significant at 95% confidence level

Table 4.3—Continued

Variable/Survey Item	Matched Pair Pre/Mid Mean Score (<i>N</i> = 56)			P- value	Matched Pair Mid/Post (<i>N</i> = 55)		
			Mean Difference			Mean Difference	P- value
After reading an article about chemistry experiment, writing a summary of the main points.	Mid	4.13	-0.02	0.908	Post	4.22	0.11
	Pre	4.14			Mid	4.11	
Learning chemistry theory.	Mid	4.02	0.07	0.610	Post	4.18	0.20
	Pre	3.95			Mid	3.98	
Writing up the experimental procedures in a laboratory setting.	Mid	4.05	0.13	0.424	Post	4.06	0.04
	Pre	3.93			Mid	4.02	
After watching a television documentary dealing with some aspects of chemistry, writing a summary of its main points.	Mid	4.18	0.09	0.592	Post	4.24	0.09
	Pre	4.09			Mid	4.15	
Applying theory learnt in a lecture for a laboratory experiment.	Mid	3.96	0.09	0.451	Post	3.96	0.06
	Pre	3.88			Mid	3.91	
Writing up the results section in a laboratory report.	Mid	4.16	0.07	0.632	Post	4.17	0.04
	Pre	4.09			Mid	4.13	
Applying chemistry concepts learnt to real-world experiences.	Mid	3.96	0.20	0.242	Post	3.91	-0.06
	Pre	3.76			Mid	3.96	

(*) Indicates the mean difference statistically significant at 95% confidence level

Findings on ANOVA indicated that GPA, Major, Hours of study per week, Years of study of chemistry, and Class level had no significant influence on students' confidence in undertaking experimental tasks based on the pre, mid, and post scores (survey #1). The F-test and p-values based on these groups are presented below:

- *GPA* (Pre: $F = 0.501$, $p = 0.683$; Mid: $F = 0.235$, $p = 0.872$; Post: $F = 1.152$, $p = 0.338$);
- *Major* (Pre: $F = 0.280$, $p = 0.757$; Mid: $F = 1.730$, $p = 0.187$; Post: $F = 0.232$, $p = 0.794$);
- *Hours of study of per week* (Pre: $F = 0.336$, $p = 0.853$; Mid: $F = 0.558$, $p = 0.694$; Post: $F = 0.699$, $p = 0.596$);
- *Years of study of chemistry* (Pre: $F = 1.464$, $p = 0.235$; Mid: $F = 0.860$, $p = 0.468$; Post: $F = 0.678$, $p = 0.569$); and
- *Class level* (Pre: $F = 1.361$, $p = 0.265$; Mid: $F = 0.904$, $p = 0.445$; Post: $F = 1.251$, $p = 0.301$).

ANOVA analysis on individual items based on pre-survey, however, revealed that a statistically mean difference between Freshmen and Sophomores ($\Delta\text{Mean} = 2.00$, $p = 0.005$), and Sophomore and Seniors ($\Delta\text{Mean} = 1.115$, $p = 0.024$) on their confidence in “ensuring that data obtained from an experiment is accurate” ($F = 4.911$, $p = 0.044$) — Freshmen and Sophomores were more confident than Seniors.

The calculated effect size (Cohen's d) (Hinkle et al., 1998) on mid/post survey # 1 mean scores was approximately 0.2 {i.e., $d = (4.03 - 3.93) / (0.666) = 0.15$ (~ 0.20)}. This implies a small mean difference between the post and mid mean scores on students' confidence in undertaking experimental tasks.

Theme 3: Students' Perceptions about, and Attitudes towards Inquiry-Based Learning Environment

Paired sample t-test comparisons between the mid and the post scores on the inquiry-based learning environment, and based on all the items indicated a statistically significant mean difference (Mid = 3.57, Post = 3.68, Δ Mean = 0.112, $p = 0.041$) — see Table 4.4. In particular, participants showed significant improvement in their perceptions about, and attitudes the inquiry-based approach in the post survey. Paired t-test analysis

Table 4.4 Shows Paired T-test Results on Mid/Post Mean Scores on Students' Perceptions and Attitudes towards Inquiry Learning Environment

Paired Samples Statistics

	Mean	N	Std. Deviation	Std. Error Mean
POST	3.6804	54	.63218	.08603
MID	3.5683	54	.62852	.08553

Paired Samples Test

	Paired Differences					t	df	Sig. (2-tailed)
	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
				Lower	Upper			
POST - MID	.11207	.39248	.05341	.00494	.21920	2.098	53	.041

results on individual survey items were grouped into five sub-themes by two individuals (with over 90% agreement reached). The sub-themes related to participants' perceptions

and attitudes towards: (1) *Activities and modules*, (2) *Instructional approach*, (3) *Teamwork*, (4) *Taking ownership in the learning*, and (5) *Ability to apply, understand the learned concepts, and communicate results*. Detailed discussions of these sub-themes are presented in the subsequent sections.

Perceptions about, and attitudes towards activities and the modules. Survey items under this sub-theme pertain to students' perceptions and/or attitudes towards the activities. Table 4.5 shows a summary of the items related to this sub-theme. Results indicate a statistical difference between mid and post scores on one item. In the post survey, participants felt that the activities were more relevant to real-world experiences compared to the mid survey (Mid = 3.54, Post = 3.85, $\Delta\text{Mean} = 0.315$; $p = 0.025$). The post mean scores indicated that participants had to work hard to complete the activities (Mid = 3.36, Post = 3.15, $\Delta\text{Mean} = -0.208$; $p = 0.213$). They also felt that the activities did not foster an environment for the development of team working skills (Mid = 3.70, Post = 3.59, $\Delta\text{Mean} = 0.111$; $p = 0.391$).

The findings also indicate that the participants strongly perceived the activities as challenging in both mid and post survey (Mid = 2.72, Post = 2.75, $\Delta\text{Mean} = 0.038$; $p = 0.832$). Positive perceptions about the activities were also noted in post scores, in which the participants strongly felt that "*the activities were more about analyzing and evaluating information than memorizing them*" (Mid = 3.98, Post = 4.13, $\Delta\text{Mean} = 0.145$; $p = 0.159$). Overall, participants showed slight improvement of their perceptions about the activities, except on two of the items, in which a negative change in perceptions was noted (see Table 4.5).

Table 4.5 Paired T-test Results on participants' Perceptions about the Activities

Variable/Survey Item	Matched Pair Mid/Post Mean Score (<i>N</i> = 55)		Mean Difference	S.D.	P-value
The activities were more about analyzing and evaluating information than they were about memorizing them.	Post	4.13	0.145	0.756	0.159
	Mid	3.98			
I felt I could not get through the activities simply by memorizing things.	Post	3.56	0.074	1.385	0.176
	Mid	3.48			
I found the activities <i>easy</i> .	Post	2.75	0.038	1.285	0.832
	Mid	2.72			
I felt I did not have to work hard to complete the activities.	Post	3.15	-0.208	1.199	0.213
	Mid	3.36			
I found the activities relevant to real-world experiences.	Post	3.85	0.315	1.006	0.025*
	Mid	3.54			
I can see how the activities relate to things that I'm interested in.	Post	3.71	0.058	0.958	0.666
	Mid	3.65			
These activities helped me to develop my team working skills.	Post	3.59	-0.111	0.945	0.391
	Mid	3.70			
These activities helped me discover what was expected of me as a learner.	Post	3.67	0.204	0.939	0.117
	Mid	3.46			

(*) Indicates the mean difference statistically significant at 95% confidence level

Perceptions about, and attitudes towards the instructional approach. Paired t-test results indicate statistically significant improvement in participants' perceptions about the instructional approaches based on mid and post mean scores (see Table 4.6). In the post survey # 2, participants felt that they were given some opportunities to formulate their own research questions during the Nanoscale science modules (Mid = 2.91, Post = 3.37, Δ Mean = 0.463; $p = 0.017$). Nevertheless, in the post survey session, they indicated that the instructor rendered them the support they needed in the learning compared to the mid-session (Mid = 3.83, Post = 4.15, Δ Mean = 0.315; $p = 0.034$).

Although the participants generally showed a slight improvement on their perceptions about the inquiry instructional approach, towards the end of the semester they felt that they needed support in establishing their own research questions (Mid = 3.17,

Table 4.6 Paired Sample T-test Results on participants' Perceptions about the Instructional Approach

Variable/Survey Item	Matched Pair Mid/Post Mean Score (<i>N</i> = 55)		Mean Difference	S.D.	P-value
During the modules, I was given opportunities to establish my own research questions.	Post	3.37	0.463	1.383	0.017*
	Mid	2.91			
I did not need support in establishing my own questions to research.	Post	2.94	-0.222	0.965	0.096
	Mid	3.17			
I did not need a lot of support from the instructor in these activities.	Post	3.30	-0.056	1.071	0.705
	Mid	3.35			
The instructor gave me the support I needed to learn in these experiments.	Post	4.15	0.315	1.061	0.034*
	Mid	3.83			
The instructor focused more on encouraging me to find information than on giving me the facts.	Post	3.95	0.182	1.002	0.184
	Mid	3.76			
I enjoyed working in this way.	Post	3.93	0.185	0.973	0.168
	Mid	3.74			

(*) Indicates the mean difference statistically significant at 95% confidence level

Post = 2.94, Δ Mean = -0.222; $p = 0.096$), as well as executing the activities (Mid = 3.30, Post = 3.35, Δ Mean = - 0.056; $p = 0.705$) compared to the mid semester activities. Table 4.2.5 shows a summary of the results on students' perceptions about the inquiry approach based on the mid and post mean scores.

Perceptions about, and attitudes towards teamwork. The paired t-test results revealed that working in groups of four; rather than two had a statistically significant impact on the participants' perceptions about "developing shared goals" (Mid = 3.61,

Post = 3.93, Δ Mean = 0.315; $p = 0.023$), and contributing towards students' learning (Mid = 3.64, Post = 3.91, Δ Mean = 0.273; $p = 0.027$). Table 4.7 shows a summary of t-

Table 4.7 Mid/Post Paired T-test Results of Participants' Perceptions and Attitudes towards Teamwork

Variable/Survey Item	Matched Pair Mid/Post Mean Score ($N = 55$)		Mean Difference	S.D.	P-value
My group worked well as a team.	Post	3.98	-0.038	0.898	0.761
	Mid	4.02			
The group was effective in developing shared goals.	Post	3.93	0.315	0.987	0.023*
	Mid	3.61			
I found the team members to be helpful in my learning.	Post	3.91	0.273	0.891	0.027*
	Mid	3.64			
I had opportunities to lead the group.	Post	3.74	0.132	0.856	0.266
	Mid	3.60			
I enjoyed working as a member of a team.	Post	3.83	0.056	0.960	0.672
	Mid	3.78			
The group worked well to overcome any difficulties or problems we encountered.	Post	3.81	-0.075	0.851	0.522
	Mid	3.89			
I can see a range of ways in which I can contribute to a group task.	Post	3.81	-0.056	0.960	0.672
	Mid	3.87			
The group appreciated my inputs.	Post	3.89	0.189	1.001	0.176
	Mid	3.70			
I developed an understanding of technical processes through working with my group.	Post	3.83	0.000	0.920	1.000
	Mid	3.83			

(*) Indicates the mean difference statistically significant at 95% confidence level

test results on mid/post mean scores on items related to “teamwork”. In summary, participants showed improved positive perceptions about teamwork on most of the items in the post survey; however, a decrease in perception mean scores were noted in three areas: “working as a team” (Mid = 4.02, Post = 3.98, Δ Mean = -0.038; $p = 0.761$), “overcoming any difficulties or problems encountered in the group” (Mid = 3.89, Post =

3.81, $\Delta\text{Mean} = -0.075$; $p = 0.522$), and “contributing to a group task through multiple ways” (Mid = 3.87, Post = 3.81, $\Delta\text{Mean} = -0.056$; $p = 0.672$).

Perceptions about, and attitudes towards taking ownership in the learning.

Analysis revealed that participants perceived more sense of ownership in their learning towards the end of the semester than in the mid-semester. Table 4.8 shows a summary of the mid/post mean score comparison results based on paired sample t-test analysis. Slight improvement on perception/attitudinal mean scores were noted on participants’ sense of control over their own learning (Mid = 3.38, Post = 3.58, $\Delta\text{Mean} = 0.208$; $p = 0.094$); confidence in their ability to establish their own research questions (Mid = 3.40, Post = 3.60, $\Delta\text{Mean} = 0.192$; $p = 0.067$); confidence in their ability to evaluate the information they have found (Mid = 3.73, Post = 3.93, $\Delta\text{Mean} = 0.200$; $p = 0.132$); and ability to evaluate different sources (Mid = 3.45, Post = 3.60, $\Delta\text{Mean} = 0.145$; $p = 0.322$).

A statistically significant difference between the mid and post mean scores was noted on one item under this category—participants indicated that they *felt they were better able to find information from different sources* (Mid = 3.22, Post = 3.67, $\Delta\text{Mean} = 1.068$; $p = 0.003$). Overall, post survey results indicated more positive perceptions (i.e. mean score > 3) about ownership in the learning.

Table 4.8 Mid/Post Paired T-test Results on Perceptions about Taking Ownership in the Learning

Variable/Survey Item	Matched Pair Mid/Post Mean Score (N = 55)		Mean Difference	S.D.	P-value
I learned how to plan my learning.	Post	3.41	0.019	0.961	0.888
	Mid	3.39			
I feel I am better able to find information from different sources.	Post	3.67	1.068	0.455	0.003*
	Mid	3.22			
I am more confident in my ability to evaluate the information I have found.	Post	3.93	0.200	0.970	0.132
	Mid	3.73			
I feel I am better able to evaluate different sources of information.	Post	3.60	0.145	1.079	0.322
	Mid	3.45			
I felt I was able to take more responsibility for my own learning.	Post	3.74	0.074	1.061	0.610
	Mid	3.67			
As a result of the activities, I am now more confident about my ability to establish my own research questions.	Post	3.60	0.192	0.742	0.067
	Mid	3.40			
I felt a sense of control over my learning.	Post	3.58	0.208	0.885	0.094
	Mid	3.38			

(*) Indicates the mean difference statistically significant at 95% confidence level

Perceptions about, and attitudes towards understanding, applying the learned concepts and communicating results. Participants showed improved mean scores in understanding the learning process, applying the concepts they learned in solving problems or issues in society, as well as communicating their findings, even though such improvement was not significant for nearly all the items (see Table 4.9). A significant improvement was noted on participants' perceptions about success in "applying the concepts they learned from the experiments in solving environmental issues in society" (Mid = 3.47, Post = 3.90, Δ Mean = 0.431; $p = 0.006$). The results also indicated that a negative change in participants' perceptions about how much they learned from laboratory course—they perceived that they learned little from the course (Mid = 3.72, Post = 3.69, Δ Mean = -0.037; $p = 0.766$).

Table 4.9 Mid/Post Paired T-test Results on Perceptions and Attitudes in Understanding, Applying the Learned Concepts, and Communicating Results

Variable/Survey Item	Matched Pair Mid/Post Mean Score (N = 55)		Mean Difference	S.D.	P-value
I feel that I understood the learning process this far.	Post	4.04	0.127	0.963	0.332
	Mid	3.91			
I did need to apply anything I learned.	Post	4.00	0.151	1.307	0.404
	Mid	3.85			
There was a lot to learn.	Post	3.69	-0.037	0.910	0.766
	Mid	3.72			
I feel more confident in my ability to solve problems.	Post	3.78	0.093	1.014	0.505
	Mid	3.69			
I can apply the concepts I have learned in this lab course in solving environmental issues in society.	Post	3.90	0.431	1.063	0.006*
	Mid	3.47			
I learned about how to present my findings to an audience.	Post	3.38	0.145	0.970	0.271
	Mid	3.24			
I feel I am better able to communicate with others.	Post	3.78	0.222	0.965	0.096
	Mid	3.56			
Any interpersonal difficulties were cleared up in a positive manner.	Post	3.87	0.132	0.962	0.322
	Mid	3.74			
I feel I am better able to present my findings.	Post	3.56	0.056	0.920	0.659
	Mid	3.50			
I was able to see good ways of presenting information.	Post	3.69	0.135	0.768	0.212
	Mid	3.56			

(*) Indicates the mean difference statistically significant at 95% confidence level

Overall, participants' perceptions about, and attitudes the inquiry learning environment improved for most items based on the post mean scores, with statistical differences noted on some items. However, the overall mid and post mean scores show that participants had positive perceptions about, and/or attitudes towards the inquiry approach (Mid = 3.57, Post = 3.68). The calculated effect size (Cohen's d) on based on the post and mid mean scores is ~0.3 — a small effect. Explanations about the observed changes in participants' perceptions and/or attitudes are presented in the discussion section.

Independent sample t-test results based on individual items indicated no statistical mean differences between the male and female participants on their perceptions and/or attitude towards inquiry-based learning environment for both mid and post mean scores (i.e., Mid: Male = 3.59, $n = 32$; Female = 3.53, $n = 23$; $p = 0.371$: $\Delta\text{Mean} = 0.06$, and Post: Male = 3.70, $n = 31$; Female = 3.65, $n = 23$; $p = 0.796$: $\Delta\text{Mean} = 0.05$). However, the results showed an increase in the attitudinal and/or perception mean scores between the mid and post tests, with male showing more positive attitudes towards the inquiry learning environment than female participants.

Independent t-test based on individual items in the mid survey revealed statistical mean differences between male and female participants on two items: *“The instructor focused more on encouraging me to find information than giving me the facts”* {Mid: Male ($n = 32$) = 4.09, Female ($n = 23$) = 3.30; $\Delta\text{Mean} = 0.789$, $p = 0.004$ }, and *“I did not need a lot of support from the instructor in these activities”* {Mid: Male ($n = 31$) = 3.61, Female ($n = 23$) = 3.00; $\Delta\text{Mean} = 0.613$, $p = 0.018$ }. While the male participants strongly felt the instructor was more of a guide than a transmitter of information in the learning, female participants were neutral about this statement. Furthermore, although positive, male participants indicated that they needed little support from the instructor compared to females.

Statistical mean differences between male and female participants were also noted for two post survey items: *“Any interpersonal difficulties were cleared up in a positive manner”* {Post: Male ($n = 31$) = 4.10, Female ($n = 23$) = 3.57; $\Delta\text{Mean} = 0.532$, $p = 0.033$ }, and *“I can apply the concepts I have learned in this lab course in solving environmental issues in society”* {Post: Male ($n = 31$) = 4.13, Female ($n = 23$) = 3.65;

$\Delta\text{Mean} = 0.481$, $p = 0.040$ }. The male participants strongly felt that interpersonal differences were amicably resolved, while female were somewhat positive about this statement. Additionally, male had strong perceptions that they can contribute towards solving environmental issues by applying the knowledge they gained in the laboratory course compared to women.

Findings on ANOVA indicated that GPA, Major, Hours of study per week, Years of study of chemistry, and Class level had no significant influence on participants' perceptions about, and/or attitudes towards inquiry-based learning environment. ANOVA results based on these groups are presented below:

- a) GPA (Mid: $F = 0.477$, $p = 0.700$; Post: $F = 0.730$, $p = 0.539$);
- b) *Major* (Mid: $F = 0.419$, $p = 0.660$; Post: $F = 1.375$, $p = 0.262$);
- c) *Hours of study of per week* (Mid: $F = 0.477$, $p = 0.753$; Post: $F = 0.533$, $p = 0.712$);
- d) *Years of study of chemistry* (Mid: $F = 0.370$, $p = 0.775$; Post: $F = 0.706$, $p = 0.553$); and
- e) *Class level* (Mid: $F = 1.944$, $p = 0.134$; Post: $F = 1.729$, $p = 0.173$).

Theme 4: Students' Perceptions about the Lab Course and Their Own Learning

Paired t-test analysis on the overall mid and post sample mean scores showed no significant mean differences (Mid = 3.796, Post = 3.845, $\Delta\text{Mean} = 0.049$; $p = 0.406$) on participants' perceptions about the course and their own learning. Results on analysis based on individual items indicated that participants had positive ($\text{Mean} \geq 4$), neutral ($\text{Mean} = 3$), and negative ($\text{Mean} < 3$) perceptions about the course, and how they learn

(see Table 4.10). Negative perceptions were noted on the organization of the lab, in which participants felt that the course was characterized by “cook-book” steps: *“Doing labs in this course was not like following a recipe in a cook-book”* (Mid = 2.64, Post = 2.89, $\Delta\text{Mean} = 0.255$; $p = 0.118$).

Furthermore, the results revealed some improvement as well as a decrease in the mean scores between the mid and post surveys, particularly on the structure of the laboratory course. For example, in the post survey, participants had negative perceptions about the course: *“Often in the lab I understood the concept behind the lab experiments”* (Mid = 3.80, Post = 3.87, $\Delta\text{Mean} = -0.073$; $p = 0.659$), and *“It was clear how the lab experiments fit into this course”* (Mid = 4.00, Post = 3.78, $\Delta\text{Mean} = -0.222$; $p = 0.083$). On the other hand, significant improvements were noted for the following items: *I like labs where I get to design an experiment to answer a question* (Mid = 3.09, Post = 3.53, $\Delta\text{Mean} = 0.436$; $p = 0.006$); and *the course provided opportunities for me to help design experiments to answer a question* (Mid = 2.89, Post = 3.76, $\Delta\text{Mean} = 0.873$; $p = 0.000$). Furthermore, participants strongly felt that *“the lab manual was well written or easy to understand* in the post than in the mid (Mid = 2.25, Post = 3.29, $\Delta\text{Mean} = 0.036$; $p = 0.814$).

There were no significant differences in the strategies the participants implemented to assess their learning or conceptual understanding before and after exposure to the Nanoscale science experiments. Overall, the participants expressed positive perceptions (Mean ≥ 4) about *“explaining ideas to someone”* (Mid = 4.48, Post = 4.30), *“applying ideas to new situations”* (Mid = 4.43, Post = 4.26), *“working*

Table 4.10 Participants' Perceptions about the Lab Course and Their Own Learning

Variable/Survey Item	Matched Pair Mid/Post Mean Score (N = 55)		Mean Difference	S.D.	P-value
Often in the lab I understood the concept behind the lab experiments.	Post	3.80	-0.073	1.215	0.659
	Mid	3.87			
I like labs where I get to help design an experiment to answer a question.	Post	3.53	0.436	1.135	0.006*
	Mid	3.09			
This course provided opportunities for me to help design experiments to answer a question.	Post	3.76	0.873	1.001	0.000*
	Mid	2.89			
It was clear how the lab experiments fit into this course.	Post	3.78	-0.222	0.925	0.083
	Mid	4.00			
Doing labs in this class was not like following a recipe in a cook-book.	Post	2.89	0.255	1.190	0.118
	Mid	2.64			
The lab manual for this course was well-written (easy to understand).	Post	3.29	0.036	1.138	0.814
	Mid	3.25			
I learn well by doing homework assignments.	Post	3.63	0.056	1.235	0.742
	Mid	3.57			
I learn well by working with my lab partner.	Post	3.85	-0.255	1.004	0.065
	Mid	4.11			
I learn well by doing hands-on activities.	Post	4.35	-0.127	0.771	0.226
	Mid	4.47			
I learn well by listening to lecture.	Post	3.44	-0.018	1.097	0.903
	Mid	3.45			
I learn well by completing lab notebooks or lab reports.	Post	3.87	0.127	1.055	0.375
	Mid	3.75			
I learn well by reading and re-reading materials.	Post	3.76	0.056	1.123	0.718
	Mid	3.70			
I know I understand when I can work problems in a book.	Post	4.17	0.037	0.990	0.784
	Mid	4.13			
I know I understand when I get a good grade on an exam.	Post	4.06	-0.093	1.170	0.563
	Mid	4.15			
I know I understand when I can apply ideas to new situations.	Post	4.26	-0.167	0.863	0.162
	Mid	4.43			
I know I understand when I can explain the ideas to someone else.	Post	4.30	-0.185	0.826	0.105
	Mid	4.48			
I know I understand when I can see how concepts relate to one another.	Post	4.37	-0.039	0.848	0.742
	Mid	4.41			

(*) Indicates the mean difference statistically significant at 95% confidence level

problems in a book” (Mid = 4.13, Post = 4.17), and *“relating concepts”* (Mid = 4.41,

Post = 4.37) as strong indicators for measuring their success in the learning—Table 4.10.

The effect size associated with the participants' attitudes towards the course and their own learning was small, that is, "Cohen's d " = ~ 0.11 .

Findings based on independent t-test indicated no significant difference in the perception mean scores for male and female participants (Mid: Male = 3.74, Female = 3.90, ΔMean = -0.166, p = 0.169; Post: Male = 3.87, Female = 3.81, ΔMean = 0.060, p = 0.671). ANOVA analysis revealed that Hours of study per week and Class level had significant influence on students' perception towards the course and/or their own learning based on the mid and the post scores, respectively—see the ANOVA results below:

- 1) *GPA* (Mid: $F = 1.646$, $p = 0.192$; Post: $F = 0.996$, $p = 0.403$);
- 2) *Major* (Mid: $F = 0.653$, $p = 0.525$; Post: $F = 0.260$, $p = 0.772$);
- 3) *Hours of study of per week* (Mid: $F = 4.722$, $p = 0.003$; Post: $F = 0.860$, $p = 0.495$);
- 4) *Years of study of chemistry* (Mid: $F = 1.975$, $p = 0.130$; Post: $F = 0.872$, $p = 0.462$); and
- 5) *Class level* (Mid: $F = 1.500$, $p = 0.226$; Post: $F = 3.941$, $p = 0.013$).

ANOVA analysis on individual mid survey items, and based on Post-Hoc tests (Tukey's test) revealed a statistical mean differences between the hours of study per week and students' perceptions about "being provided with opportunities to help design the experiments" (Mid: $F = 4.273$, $p = 0.005$), and assessing their understanding by "doing homework assignments" (Mid: $F = 5.823$, $p = 0.001$). Differences in the mean were mainly noted between participants whose study hours were 16 to 24 hrs and 6 to 10 hrs ($\Delta\text{Mean} = 1.100$, $p = 0.026$), and 11 to 15 hrs ($\Delta\text{Mean} = 1.145$, $p = 0.022$) — "*being provided with opportunities to help design the experiments.*" This means that participants

who studied between 16 to 24 hrs had significantly higher mean perception scores on this item. Furthermore, significant mean differences on assessing participants' conceptual understanding by doing homework assignments were noted between participants who study less than 6 hrs per week and those who study 6 hrs and beyond. That is, 1-5.9 and 6-10.9 yrs ($\Delta\text{Mean} = 1.667$, $p = 0.001$), 1-5.9 and 11-15.9 yrs ($\Delta\text{Mean} = 1.750$, $p = 0.001$), 1-5.9 and 16-24.9 yrs ($\Delta\text{Mean} = 1.350$, $p = 0.018$), and 1-5.9 and >24.9 yrs ($\Delta\text{Mean} = 1.568$, $p = 0.003$). Participants who studied less than 6 hrs had a lower perception mean than those who studied 6 hrs and beyond.

ANOVA findings based on individual items of the post survey indicated significant mean difference on participants' perceptions about "helping design an experiment to answer a question" (Post: $F = 3.091$, $p = 0.035$), and the presentation of the lab manual—"The lab manual for this course was well-written (easy to understand)" (Post: $F = 4.389$, $p = 0.008$). Post-hoc tests revealed the significant mean differences between Freshmen and Juniors ($\Delta\text{Mean} = 1.762$, $p = 0.017$) on the latter item above—Freshmen strongly felt that the manual was well written (easy to understand) compared to Juniors.

Findings on participants' perceptions about the course and their learning based on the open-ended survey items revealed a variation in perceptions about the experiments. The subsequent sections is a discussion on participants' perceptions about the experiment they learned the most from, the experiment they learned the least from, and that which had relevance to their daily-lives and/or society. Underlying reasons for the identified experiments based on the aforementioned categories are presented under the discussion section.

Experiment learned the most from. Twenty three (~38%) of the participants felt they learned the most from the “nanotechnology experiments” compared to individual conventional experiments (see Table 4.11). One participant (~2%) also indicated “nanotechnology experiments and Gravimetric determination of aluminum” as the most experiments learned from. Based on the conventional experiments, thirteen of the participants (~27%) felt they learned the most from the “titration of calcium & zinc” experiment; four participants (~8%) stated “potentiometric titration of acid”; three (~6%) indicated “fluorometric determination of aluminum”; two participants (~7%) highlighted “Gravimetric determination of sulfate”; and others highlighted calibration of glassware (1), Gravimetric determination of nickel and volumetric determination of soda (1), and Gravimetric determination of nickel (1). Moreover, two of the participants (~ 4%) stated that they did not learn much from any of the experiments, and one participant felt that she learned from all the experiments.

Experiments learned the least from. Results on perceptions about “the experiment learned the least from” showed that 19 out of 55 participants (~ 35%) stated “calibration of glassware”; five stated “titration labs” (~16%); and three (~ 6%) “potentiometric titration of acid” and “nanotechnology experiments” (~ 6%). Other responses were: “nanotechnology labs” (~ 4%); “gravimetric determination labs” (~ 4%); “fluorometric determination of aluminum” (~ 4%); “non-nanotechnology labs” (conventional experiments) (~2%); “calibration of glassware & potentiometric titration of acid” (~2%); “gravimetric determination of sulfate” (~2%); and “gravimetric determination of nickel” (~2%)— see Table 4.11. Additionally, two of the participants

Table 4.11 Participants' Perceptions about the Quantitative Chemistry Laboratory Course Experiments

	Frequency N = 55	Valid Percent (%)
Experiment learned the most from		
Nanotechnology experiments	23	38
Titration of calcium & zinc	13	27
Potentiometric titration of acid	4	8
Gravimetric determination of nickel	1	2
Fluorometric determination of aluminum	3	6
Gravimetric determination of sulfate	2	4
None	2	4
Gravimetric determination of nickel & volumetric determination of soda	1	2
Volumetric determination of soda	1	2
Calibration of glassware	1	2
Nanotechnology experiments and Gravimetric determination of aluminum	1	2
All	1	2
No response	5	9
Experiment learned the least from		
Calibration of glassware	19	35
Titration labs	5	9
Potentiometric titration of acid	3	6
Nanoparticle experiments	3	6
Nanotechnology lab 1	2	4
Gravimetric determination labs	2	4
Fluorometric determination of aluminum	2	4
Titration of calcium & zinc	2	4
None	2	4
All	2	4
Non-nanotechnology labs [Conventional labs]	1	2
Calibration of glassware & potentiometric titration of acid	1	2
Gravimetric determination of sulfate	1	2
Gravimetric determination of nickel	1	2
No response	9	16
Experiment most relevant to modern society		
Nanotechnology labs	38	69
Titration of calcium & zinc	2	4
HPLC [determination of caffeine in coffee]	2	4
None	2	4
Most of the labs	1	2
Gravimetric determination of sulfate	1	2
Potentiometric titration of acid & gravimetric determinations	1	2
All	1	2
All with the use of equipment	1	2
No response	6	11

(~4%) pointed out that they learned the least from all the experiments, whereas two (~4%) felt they learned from all the experiments (all the experiments were helpful).

Experiment most relevant to student's daily-life and /or modern society. A significant number of responses, thirty eight of the participants (~69%), indicated that among all the experiments, nanotechnology-chemistry experiments were the most relevant to their daily-lives and/or modern society. Others highlighted “titration of calcium & zinc” (2); “HPLC (determination of caffeine in coffee) (2); “none” (2); “most of the labs” (1); “gravimetric determination of sulfate” (1); “potentiometric titration of acid & gravimetric determinations” (1); “all [experiments]” (1); and “all with the use of equipment” (1)—Table 4.11.

Chapter Summary

In this chapter, I have presented the findings based on students' demographic information— gender, GPA, Major, Class level, hours of study per week and years of study of chemistry. I have also presented findings of the three survey instruments, including the open-ended survey items, employed in the collection of data in the current study. Four main themes have been reported based on the survey scores: students' perceptions about chemistry (Theme 1), students' attitudes (confidence) towards undertaking experimental tasks (Theme 2), students' perceptions about, and attitudes towards inquiry learning (Theme 3), and students' perceptions about, and attitudes towards the quantitative laboratory course and their learning (Theme 4).

Results based on theme 1 indicated a decrease in mid perception mean scores in comparison to pre, with significant mean differences noted on students' perceptions about

chemistry jobs. At the beginning of the semester, students felt that chemistry jobs were more interesting and exciting, but these perceptions significantly changed following exposure to the conventional experiment. Results also indicate a slight improvement of students' perceptions about chemistry on most post survey items compared to the mid and pre survey scores. Statistical mean differences between the mid and post scores were noted on students' perceptions about the flexibility of chemists' ideas, and chemistry websites. In the post survey, the participants felt that chemists are more flexible in their ideas, and that chemistry websites are more interesting compared to their perceptions during the mid semester.

Overall, most participants had positive perceptions about chemistry (Mean > 4) based on the pre, mid, and post scores. Class level had a significant influence on students' perceptions about chemistry for some pre and post items. In particular, Freshmen and Sophomore students had more positive perceptions about "*chemistry jobs being satisfying, and interesting*" than Seniors. Results also showed that Freshmen had more positive perceptions than Seniors on "*Chemistry websites being interesting*."

Results on students' confidence to undertake experimental tasks (theme 2) indicate no significant improvement over the semester. However, a significant improvement on students' confidence in "designing and conducting a chemistry experiment" was noted in the post survey compared to the mid survey. Male had more confidence than females over the semester, with significant mean differences often noted prior to the introduction to the laboratory course. Towards the end of the semester (post-survey), males had significantly higher confidence about "applying chemistry concepts learned to real-world experiences" than females did (Post: Male = 4.09, Female = 3.61,

$\Delta\text{Mean} = 0.482$, $p = 0.030$). However, females showed more improvement on their confidence over the semester compared to males. Post-Hoc analysis (Tukey's test) revealed that Freshmen and Seniors were more confident than Sophomores in "*ensuring that data obtained from an experiment is accurate*" ($F = 4.911$, $p = 0.044$). Overall, students had more positive attitudes ($\text{Mean} > 3$) towards undertaking experimental tasks at the end of the semester (post) compared to the pre and mid semester (Pre = 3.96; Mid = 3.93; Post = 4.03).

Nevertheless, results indicate significant improvement on students' perceptions and attitudes towards inquiry in the post survey. Significant improvements were noted on students' perceptions about (1) the relevance of the activities to real-world experiences; (2) opportunities to establish research questions; (3) instructor's support in the learning; (4) effectiveness of group learning in developing shared goal; (5) group support in the learning; (6) ability to find information from different sources; and (7) ability to apply the concepts learned in the course to solve environmental issues in society.

Results on perceptions about the course and student learning revealed that students liked designing experiments more in the post. Additionally, they indicated that the course afforded them opportunities to help design experiments. Overall, males had stronger perceptions about chemistry; confidence undertaking experimental tasks; perceptions about, and attitudes towards inquiry learning; as well as the course and their learning than females. The calculated effect size based on the mid and post mean samples on the three survey instruments is small, $d < 2.0$.

In the next chapter (i.e., Chapter 5), I discuss reasons and/or factors that led to the observed change in perceptions about chemistry; attitudes towards undertaking

experimental tasks; perceptions about, and attitudes towards inquiry environment; as well as perceptions about, and attitudes towards the laboratory course and student learning.

The discussion focuses on negative and positive change in perception and/or attitudinal scores based on individual survey items, as well as general perceptions about the course.

Overall, qualitative findings have been employed (in Chapter 5) to inform the interpretation of quantitative findings reported in Chapter 4.

CHAPTER 5 : DISCUSSION OF RESULTS

Introduction

This chapter presents a discussion on the interpretation of the quantitative results (i.e., results presented in Chapter 4) using qualitative results. Discussion is focused on reasons or factors causing the perception and attitudinal change tailored around the 4 themes previously discussed, as well as the results of the open-ended survey items. In particular, findings on students' general perceptions about the quantitative chemistry laboratory course based on the qualitative data (i.e., interviews and classroom observations) as well as follow up interview findings on selected survey items, including open-ended survey responses have been triangulated to support validity of the claims made by the researcher. The discussion has been narrowed to items demonstrating significant change in perception or attitudinal scores, and negative and positive change in perceptions or attitude, including interesting observations not anticipated by the researcher. The selection of items for discussion is based on the criterion that at least two participants were interviewed on the selected item(s). It is also important to note at the outset that not all the survey items were followed up on in the interviews.

Theme 1: Interpretation of the Quantitative Results: Reasons/Factors for the Observed Change in Students' Perception about Chemistry

The results showed a significant improvement on student perceptions about chemistry: "*chemists' flexibility in their ideas*" and "*chemistry websites being interesting*". Additionally, negative and positive changes in perceptions were noted, even though the change was insignificant. In the subsequent sections, I discuss the underlying

factors for the observed significant change in perceptions in the aforementioned areas, as well as factors for negative and positive change on chemistry research and jobs.

Furthermore, I will discuss the underlying factors on students' perceptions *about* “*chemistry jobs being challenging*”, as the mean score on this item was very low, that is, less than 3—an observation that is interesting, and not anticipated by the primary researcher. Uncovering participants' perception about chemistry research and job is crucial, as preparing competent scientist for the future workforce is one of the main goals of science education.

Chemists are flexible in their ideas—significant improvement. Findings on participant change in perception indicated that the nanotechnology experiments positively influenced participants' perceptions about the flexibility of chemists in their ideas. In particular, the structure of the experiments and/or the lab course— ‘cook-book’ versus inquiry, and the concepts being learned influenced the participants' change of perceptions. For example, Participant M01 (a male junior chemistry major) expressed that prior to the nanoscale science-based experiments, he thought that chemists have to use a standard method in doing chemistry research. Putting himself in the shoes of a chemist, he lamented the repetitive method of conducting laboratory experiments, in which the routine is writing pre- laboratory outlines geared towards familiarizing students with the experimental set-up, following recipe-type experimental procedures, and writing laboratory reports (i.e., the structure of experiments and/or the course). For M01, the structure of the conventional experiments in this course mirrored his previous laboratory courses which led him to initially believe that chemists are less flexible in their ideas (mid-survey).

Following the exposure to the nanotechnology experiments (post survey); he changed his perceptions and viewed chemists as flexible in their ideas. He expressed that the nanotechnology experiments afforded him an opportunity to come up with a sound procedure to investigate a research problem, and search for relevant information to explain the chemical principles underlying the observed phenomenon without being “spoon-fed” with all the information by the instructor. An example of an interview excerpt demonstrating this change in perception is presented below:

R: Based on the mid survey, you felt that “chemists are fixed in their ideas”, but on the post survey you indicated that “chemists were more flexible in their ideas”. Could you explain why you changed your perceptions?

M01: Before this lab, I had already taken general chemistry and organic chemistry labs and the lab methods that were given in those were very similar to the non-nanotechnology methods that we used in this course too. So you know years now I have just been used to making a prelab, showing up in the lab, following the recipe and then writing the lab report by putting your data [together]. Until I had seen the nanotechnology labs, I realized that you are given the freedom to make your own method; use your own chemical knowledge to increase your accuracy and design the lab itself.

Furthermore, M01’s initial view that chemists are less flexible in their ideas seemed to rest on the belief that scientific knowledge is informed by scientific laws (i.e., concepts learned, or being learned), which do not change. However, he indicated that his experience with the nanotechnology labs was a reflection of how a scientific research is conducted in real-life, and that scientific concepts, including laws are not written on stone; rather they are constantly being researched on, and often improved. He said:

[Following the exposure to the nanoscale science-based experiments] It kind of occurred to me that this is kind of what it goes in real-world. You are always trying to learn more,

make the reaction more efficient, and increase your yield and what not in real-life, instead of just going into the lab and doing your work and leaving. That's more indicative of chemists being fixed in their ideas where scientific laws that have been laid down don't change, whereas it's not the case they are being researched on all the time and trying to make them better. (M01)

Like M01, participant M31 (also a male junior chemistry major) stated that his initial view that chemists are less flexible in their ideas were due to prior knowledge about the already discovered scientific laws and ideas that have to be learned and re-learned and followed as rules in the learning process. His experience with nanoscale science-based experiments, that is, the introduction to the nanotechnology concepts fully convinced him that new discoveries are being made, and that ideas are subject to change. He argued that all scientists, including chemists, should not have their ideas fixed on the already discovered scientific concepts and laws, instead they should be flexible. An excerpt illustrating M31's perception change on this item is provided below:

R: "Chemists are fixed in their ideas." Mid (score = 5), post (score = 7). Please explain why you changed your perception.

M31: I think what I was thinking of at the time [mid survey] was that whenever we learnt chemistry we learnt mostly about laws and ideas that have already been discovered and that we just kind follow as rules, whereas after we did the nano technology labs I kind of got an idea that not everything is discovered. I think I knew that before but doing those labs made it more apparent to me and prominent in my mind [that] ideas can change. Not just chemists but all scientists need to be flexible in order to be good scientists.

Similar arguments were echoed by participant M15 (a female junior physics major), who felt that the conventional experiments only exposed her to one method of carrying out laboratory activities, in which she was not required to critically think, instead she had to follow well outlined procedures to complete her laboratory investigations. Exposure to the nanotechnology labs, however, led her to experience critical thinking, as well as divert from the norm by designing experimental procedures without much assistance from the instructor. Such experience convinced her that chemists do not use a single method—following step-by-step procedure to investigate a research problem; rather they use different methods while being guided by their critical thinking skills to do research. See the interview excerpt below:

R: “Chemists are fixed in their ideas.” Mid (score = 5), post (score =7). Please explain why you changed your perception.

M15: Basically in the beginning [by mid semester] it was more of just doing the same thing over and over again like the normal labs. It was just like “you gonna do this, you gonna do that [referring to well outlined procedures].” You really not gonna think critically about what you’re doing, or how this interacts with society as a whole. Going with the nanotechnology labs you had to actually think yourself; you had to do this, or I could do this. It’s more at that point I felt chemists are more flexible to, you know, change their ideas; they didn’t have to do the same thing over and over again. They could change that a little bit. That’s what I appreciated about those labs [nanotechnology] because they gave me a new perspective of what chemists are like thinking.

Other participants also highlighted nanotechnology experiments as the main influence for the change in perception about the flexibility of chemists in their ideas. Overall, the

novelty of the nano concepts and the learning approach inquiry embedded in the nano modules had a significance influence on students' perceptions about chemists.

Chemistry websites are interesting—significant improvement. Results on pre/mid and mid/post mean score comparison on this item showed that prior to the introduction to quantitative lab course, students had slightly positive perceptions about chemistry websites compared to their perception after exposure to the conventional experiments (Pre = 4.98; Mid = 4.63). Students expressed more positive perceptions in the post than the mid survey (Mid = 4.64; Post = 5.15). A significant positive mean difference was observed in the latter comparison, with a strong p-value (i.e., $p = 0.003$ with α set at 0.05). Interview participants who showed a positive change in perception for this item referenced nanotechnology experiments as the main factor for the observed perception change. Some participants stated that prior to the nanotechnology experiments, they perceived that chemistry websites were not interesting (e.g., M01), and that they only visited websites if the concepts were complex for the conventional experiments (e.g., M31). However, the design of the nanotechnology experiments “forced” them to search for relevant resources to prepare for the lab lesson, and complete their laboratory reports. Examples of interview excerpts are provided below:

R: “Chemistry websites are interesting.” Mid (boring), post (interesting). Explain why you changed your initial perception.

M15: Especially with the nanotechnology labs, it made you go out and do more research. So it actually made me go onto chemistry websites and figure out “oh this is what this does” kind thing. They were much more helpful than I had preconceived in the beginning. It just made me go out and discover more on the internet. So, originally [in mid], they [chemistry websites] were not fun as I thought.

R: "Chemistry websites are interesting." Mid (boring), post (interesting). Explain why you changed your initial perception.

M31: Well before the nano technology labs, I only visited chemistry websites when I was struggling with like an idea so I was just viewing general education websites but as we got to the end of the labs [nanoscale science-based experiments] we were asked to research a little bit before you came in on your own [required to design experiments]. Although I didn't do much research, the sites that I did end up visiting were very interesting. They were more relevant and it wasn't just an explanation of how to do something but more of an idea or someone's work that they had done and that was quite interesting to read. But I know that there is a broad spectrum of chemistry websites out there.

A search on more related concepts (i.e., the two nanoscale science-based experiments), and the content presented in the articles, perceived to be interesting, triggered their positive view about chemistry websites.

M01: researching a method to use for the labs was definitely the most intriguing part. I did a lot of SciFinder searches for gold nano particles and when researching for that I found quite a few very good articles which I referenced in my lab report. That was very helpful.

M31: ...as we got to the end of the labs [nanoscale science-based experiments] ... the sites that I did end up visiting were very interesting. They were more relevant and it wasn't just an explanation of how to do something but more of an idea or someone's work that they had done [the content] and that was quite interesting to read. But I know that there is a broad spectrum of chemistry websites out there.

Results showed that nanotechnology had a significant influence on students' perceptions about chemistry. In particular, the novelty of the nano concepts and the inquiry-based learning approach embedded in the nano modules had a significant positive impact on students' perceptions about chemists and chemistry websites. If institutions of higher learning are indeed concerned about the production of future chemists for the required workforce in chemical industries, then the first step is to make students feel as chemists in a chemistry classroom setting. This could be achieved by implementing chemist-like practices during the learning process. In a real-world setting, expert scientists, including chemists, do not often follow written procedures to solve a scientific problem; rather they critically think, search for relevant information to help them plan and develop procedures in an attempt to provide solutions to the problems. These real-world practices should also translate into the undergraduate STEM classrooms. That being said, there is a need to reinforce scientist-like practices in the science classrooms.

Chemistry research solves problems—positive change. It goes without saying that solving scientific problems and issues faced in the current and future society lies in the hands of expert scientists. Science education strives to prepare competent problem-solvers in contemporary society. Therefore, it is imperative that science majors be taught problem-solving skills that translate to the real-world experiences. This could be fully achieved if their perceptions about the play of chemistry research in solving problems are understood. Results in the previous chapter showed that students had positive perceptions (Mean > 4) that “chemistry research solves problems. In particular, a positive change in perception was observed between the mid and post scores on this item, even though the change was not significant.

One explanation of the insignificant change is that some of the participants might have been less positive about their perceptions on this item. Of the two participants interviewed on their perceptions about this item, one (M15) had a positive, and the other (M04, a male senior biochemistry major) had a negative change in perception, based on the mid and post scores. The participant with the positive perception in the post (M15) highlighted the nanoparticle-pesticide experiment (nanotechnology-chemistry module # 2) as the main influential factor. In the mid, she had the perception that chemistry research solves and creates problems in society. However, following the second nanoscale science experiment, she was convinced that while chemistry research creates problems, the overall goal it seeks to address is solving the problem—increasing crop yield. With reference to this experiment, she acknowledged that although pesticides, designed and manufactured through chemistry research, may have adverse effects to human the contributions they make in improving crop yield for society outweigh the adverse effects. See the interview excerpt below:

R: “Chemistry research solves problems in society”. Mid (positive perception, score = 6), post (Strong perceptions, Score = 7). Please explain why you changed your perception.

M15: I think in mid, I was thinking just differently it was more chemistry solves problems but also creates problems. Let’s say, you are creating pesticide, so that’s something for society, so then you put on the crops and unfortunately it affects them, you have to go back and change. In post, I thought it really solves problems, even though it may create problems but the main goal is just solve problems. It’s not to actually create problems. Yes, there might be adverse effects but we are aiming to actually better society with that.

In contrast, M04 indicated that the nanoparticle-pesticide influenced her change in perception. While he initially felt that chemistry research solves problems in society and scored this item 6 out of 7, the nanoscale science experiment #2 made him change his perception neutral. He expressed that although chemistry research solves problems in society, it equivalently creates problems.

R: "Chemistry research solves problems in society." Mid (positive perception, score = 6), post (neutral, Score = 4). Can you explain why you changed your perception?

M04: I think at first [mid survey] I was thinking that chemists solve problem; they fix things but then after we had some nano units I realized that while they fix these problems, they also create problems. Like for pesticides you could synthesize a pesticide and do a chemistry duty and do something good because you're trying to improve a yield of the crop, but then you create a problem. That's when I decided when I thought of it was "no it is at the middle" because some of the solutions to some problems are the real cause to the creation of a new problem.

Chemistry research helps people—negative change. A follow-up interview on this item also revealed that while some participants felt that chemistry research harms people (e.g., M31, a male junior chemist; and M42, a female junior biochemistry major), others felt that it helps people (e.g., M65, a female junior biochemistry major). Although the observed change was insignificant, it could be inferred that those who had negative perceptions based on this item exceeded those with positive perceptions. The main factor for the slight negative change in perception as explained by M31 and M42 was the nanoparticle-pesticide experiment. Like M04, these students felt that while pesticides are useful in improving crop yield, they are detrimental to human health.

R: "Chemistry research helps people". Mid (score = 7), post (score = 6). Can you explain why you changed your perception?

M31: Chemistry definitely helps people however after thinking about it, it's not just that it helps people sometimes pesticides help people but they can also harm people. Am still saying that they do help people but sometimes people in general don't think of the consequences of their actions so for instance making pesticides may improve your crop yield it can also hurt people without really realizing it. So the idea of chemistry is to further society but there are some repercussions and it's good to try and be aware of that.

R: "Chemistry research helps people". Mid (score = 7), post (score = 6). Can you explain why you changed your perception?

M42: Because in mid I didn't get introduced to pesticide, but in post I have the pesticide and I learned pesticide can harm people if it has more concentration itself. So the pesticide is made by a chemist, even though it's making the crop yield better, people get more food, but on the other hand it could harm too. So it's not 100% improve the society. It mostly improves, but sometime too it cannot improve.

For M65, her perception about the contribution of chemistry research in helping people was neutral. Like M04, she initially felt that chemistry research helps as well as harms people. Following exposure to published research articles and other resources, she learned that the benefits of chemistry research in people's lives outweigh the cons. Overall, her positive change in perception was influenced by the information she gathered from published research work and other resources. See a portion of the excerpt below:

R: "Chemistry Research helps people." Mid (neutral = 4), Post (helps, score = 6). Explain why you changed your perception?

M65: In the mid I was thinking that that chemistry helps and harms people depending on what is going on, but then as I went on, I think it helps more people than it's gonna harm. In my head I went on and reading chemistry papers and whatever I was like "you know, it's gonna help more people than it's gonna harm."

Chemistry research advances society—an interesting finding. Scientific research is geared towards advancing society, and/or providing solutions to issues facing the society. Students' perceptions on this item were very interesting to the researcher because the participants demonstrated negative change of perceptions based on the pre/mid and mid/post mean comparisons. While it is important to uncover the underlying factors for the observed phenomenon, none of the interviewed participants had a negative change in perception about the role of chemistry research in advancing society. Most students had a neutral perception, or a positive change in perception between the mid and the post scores.

Findings of the interview analysis based on one of the interview participant who showed a positive change in perception M15—a female, Junior physics major) indicated that nanotechnology experiment # 2 (i.e., the nano-particle pesticide lab) influenced her improvement on perception about the role of chemistry research in advancing society. She felt that conducting research to determine the concentration of pesticides in food items is important in ensuring that the adverse health effects of pesticides in humans are controlled. Her involvement in this "chemist-like" practice improved her perception about the advancement of society through chemistry research—see the dialogue between the researcher and participant M15 below:

R: "Chemistry research advances society." Mid (advances, score = 6), post (strongly advances = 7). Please explain why your perception changed?

M15: It was kind the same deal as the one above. Yes, its main goal is to advance society but also can injure it at times. And then a couple of the experiments were more of, you know, we really are trying to do good things. We are trying to advance society; that's the main goal; trying to help people, to better society.

R: Could you give me an example of the experiment where you were able to realize that chemistry research advances society?

M15: Yes, it was specifically the pesticide one. It was to advance society; it is trying to help people because we were trying to figure out the concentrations of pesticides, so it is trying to protect people from adverse health effects, so it advances society in that way. So just getting the background from that specific experiment really put in my mind "you know we are helping people with what we are doing", so it's kind what I was going with.

Overall, following the nanotechnology experiments, participant M15 positively improved her perceptions about the role of chemistry research in advancing society, solving problems, helping people, and improving the quality of life.

Chemistry research improves the quality of life—an interesting finding.

Although none of the interviewed participants had a negative change in perception based on this item, three of the interviewed participants with positive change in perception based on mid and post score differences pin-pointed nanotechnology-chemistry experiments as the influential factor for their perception change. For instance, M20 (a female sophomore chemistry major) felt that nanotechnology plays an important role in improving chemistry research, as well as the social aspect of life. She said:

R: "Chemistry research improves the quality of life". Mid (6= improves), post (7= Improved more). Explain this change in perception.

M20: The only thing I could probably think of as in to why I would think a little less of it improving the quality of life would be, if, if you take like, I guess a nanoparticle lab, like the nanoparticle has a lot to do with, this new, this new thing that came into improving the research of chemistry. And with that, it has a lot to do with like you know obviously as well technology. And the way that I think of technology, if you think about it, it also deals with a lot of like, like technology itself maybe a little bit more like the social aspect of life.

Her ideas might have also stem from the introduction of the key role played by nanotechnology in contemporary society. Participant M56 (a male senior chemistry major), also perceived that the nanotechnology experiment influenced his perception that chemistry research improves the quality of life. He highlighted by sharing ideas with his peers (group discussion), and realizing the pros and cons of pesticide use in society made him aware and proud of the chemistry profession in mitigating problems related to scientific research in attempt to improve the quality life. His interview excerpt illustrating this argument is provided below:

R: "Chemistry research improves the quality of life." Mid (improves = 6), Post (strongly improves = 7). Explain this change in perception.

M56: Again, I'm studying to be a chemist, and I think at the beginning [mid] I was thinking that certainly there are chemicals that are harmful to use. Towards the end of the course it might be because we talked more about the nanoparticles and pesticides and I had a control over it and seeing my other students in the class talking about how we have to use pesticides and their dangers it made me feel good about how chemistry as a profession is kind really trying to control the negative consequences of what we do.

Chemistry jobs are challenging— an interesting finding. The ultimate goal of education is to get jobs that can sustain us, while making advancements in society. Out of

the 56 participants who completed this item based on the post survey, only one participant had the perception that chemistry jobs are easy (score = 5). Nine participants (16%) had a neutral perception, while the rest (46 participants ~ 82 %) had the perception that chemistry jobs are challenging (score < 4). The interview findings revealed a range of factors that influenced students' perceptions about the easiness of chemistry jobs. For example, participant M65 expressed the *"high level of knowledge and skills required in handling chemical instrumentation"*. This factor stemmed from her laboratory experience with chemical instrumentation in which she was felt inadequately prepared to handle some chemical instrumentation.

R: "Chemistry jobs are challenging." Mid (challenging = 3), post (somewhat challenging = 4). Explain why you changed your perception?

M65: I think when I started there were are challenges and I don't have the experience like I didn't know the techniques, but with time I was like "these are using the same technique." So, I felt it wasn't challenging, but it's not going to be easy because still have to use your knowledge of equip and stuff you have to do the job.

Likewise, participant M63's (a male senior geology major) perceptions were influenced by his *laboratory experience*, in which he felt that a lot of knowledge is needed for chemistry jobs, as well as knowledge transfer to other fields.

R: "Chemistry jobs are challenging." Mid (very challenging = 2), post (challenging = 3). Explain why you changed your perception?

M63: I have never had a professional chemistry job, but I can relate to my laboratory experiences. So as far as working on my laboratory experiences, it is challenging in many aspects and it requires a lot of learning and basic knowledge, and the progression of knowledge into different fields and aspects.

Participant M56 (a male senior chemistry major) highlighted that chemistry jobs are more challenging because *chemistry is a hard-science*. He also expressed that chemistry jobs, like other science jobs need a *high level of knowledge as well as training* compared to non-science jobs. Overall, he held the belief that sciences, including chemistry, are challenging subjects.

R: "Chemistry jobs are challenging." Mid (very challenging = 2), post (very challenging = 2). In your opinion, could you explain why you feel chemistry jobs are challenging?

M56: Honestly it [chemistry] is one of the hard-sciences. It's not easy to get the point that there are plenty of other jobs that you can do that are easier to get some level of training, get some level of knowledge. I know a lot of people, and I believe anybody if they work hard enough can do it. At the same time, I feel it's very challenging to do a science like this, and understanding the possible sources of errors. I think if it's doing chemistry it's going to be challenging, and conceptually in terms of the environment, science is definitely challenging.

Finally, participant M55 (a male junior biochemistry major) perceived that chemistry jobs challenging because they involve answering questions that have not been researched on, and that need critical thinking to answer through scientific investigation. It is probable that her laboratory experience in conducting experiments to investigate a problem triggered this perception. An example of her interview excerpt is shown below:

R: "Chemistry jobs are challenging." Mid (challenging = 3), post (challenging = 3). Explain why you held this perception.

M55: Because they require you to answer questions that people really don't understand, so you have to feel challenged to figure out things that people don't know.

In summary, changes in student perceptions about chemists, chemistry websites, and chemistry research were highly influenced by the nanotechnology experiments. The researcher noted that student perceptions about “easiness of chemistry jobs” was mainly influenced by laboratory experiences, especially on the level of knowledge required to (1) understand chemical principles, (2) answer research questions, and (3) operate chemical instrumentation. Also, the perception that chemistry is a “hard-science” influenced one participant’s perception.

Theme 2: Interpretation of the Quantitative Results: Reasons/Factors for the Observed Attitudinal Change in Undertaking Experimental Tasks

In this section, I discuss the factors that led to the significant change in students’ confidence (attitudes) in designing and conducting a chemistry experiment, as well as the non-significant change between the post and mid mean scores on selected items. It is important to note that some participants were interviewed to investigate their individual change, even though there was no statistically significant change for the whole sample. Thus, the factors for the non-significant items may, or may not be generalizable to the sample of the participants who did not participate in the interview, yet showed negative or positive change in attitude, in this case confidence, based on these items. The two items displaying negative change in confidence are: “Determining what answer is required from a written description of a chemistry experiment”, and “Applying chemistry concepts learnt to real-world experiences”. A discussion on the positive attitudinal change centers on confidence in “reading the procedure and conducting the experiment without supervision.

Designing and conducting chemistry experiment—significant change.

Quantitative results indicated that most participants had a more positive attitude towards designing and conducting chemistry experiments in the post survey compared to mid survey (Mid: Mean = 3.38; Post = 3.71, $p = 0.007$). A majority of the participants interviewed attributed the observed positive change to the nanotechnology experiments. The interview findings revealed that most students, even seniors, had no prior experience in designing and conducting laboratory experiments with little guidance from the instructor. In the mid survey (i.e., after exposure to normal experiments), most of the students were undecided about their confidence in designing and conducting experiments. One explanation for this observation may be due to the structure of the normal experiments in which students are provided with well outlined procedures for the experiments in addition to the instructor reiterating the steps and telling them the expected outcomes. Therefore, the idea is to verify scientific concepts presented in the manual and/or from the instructor's demonstration.

The classroom observations also revealed that a few students were initially less confident and reluctant to engage in a discussion on how to come up with an experimental procedure for synthesizing gold nanoparticles. For instance, participant M03 (a male senior chemistry major) initially felt that he could not come up with the ideas on the experimental set up, as he had no prior experience in developing procedures in a laboratory setting. The TA had to push him to give it a try by reminding him that he will be expected to design experiments on his own in a real job setting. Below is a dialogue between the TA and M03 illustrating M03's lack of confidence in engaging on the development of a procedure to synthesize nanoparticles:

M03: I am used to being told what to do, so I don't know how I can design the experiment.

TA: One day you will be at work and asked to formulate a procedure.

M03: My boss will tell me what to do.

TA: Actually you may be the boss and you wanna formulate the procedure.

M03: I guess that makes sense. I will have to think of a procedure myself. (Source: Classroom Observations)

Although he engaged in developing a procedure with his peers, his mid and post survey scores on this item showed that he was undecided on his confidence in designing and conducting an experiment without supervision. Similarly, M54 initially hated the idea of designing experiments. She, however, liked the experience after realizing that he could come up with a procedure with her peers. Based on the interview findings, she said:

R: Describe your experiences in learning through the inquiry-based approach, where you were given opportunities to design procedures.

M54: I hadn't had a lot of experience of designing an experiment before this course, so it was something new to me to actually think about the entire experiment. It was experience. I didn't like it at the beginning because I didn't really want to design but when we were actually given a chance to do it I liked that; I had to think about it. So it was a good experience.

Students' attitudinal scores in the post indicated that some students were somewhat confident in undertaking these tasks, while others felt totally confident. They asserted that the Nanoscale science experiments afforded them opportunities to come up with a procedure for the experiment without the TA telling them what to do. In addition, some stated that sharing ideas with their peers in groups was very beneficial. Overall,

most students had no prior experience with designing of experiments, but appreciated the experience and developed confidence after realizing that they can successfully design a procedure on their own. Illustrations of how nanotechnology experiments influenced students' improvement in confidence towards these two areas are presented below.

R: (Confidence) 2C— “Designing and Conducting a chemistry experiment”: Mid (somewhat confident), post (totally confident). Explain why your perceptions changed.

M01: I have always been used to following instead of, you know, more of leading a research group, or leading myself to design a lab, or to run a lab. Until I had done the nanoscale science-based experiments, I hadn't had any experience doing that and once I had done that and seen how easy it was; how much more enjoyable the labs were, I felt more confident than before doing those nanoscale science-based experiments in designing my own methods.

R: (Confidence) 2C— “Designing and conducting a chemistry experiment”: Mid (undecided), post (somewhat confident). Explain why your perceptions changed.

M15: Because the nanotechnology ones gave me a chance to take control of my procedure, that I could personally control what was happening, conduct the experiment myself kind thing. It wasn't just following recipe get it done; I had to think critically about “this is what I need to do to have this happen, that kind stuff”. I just gave me more confidence and being able to conduct one myself.

R: (Confidence undertaking tasks) 2C— “Designing and conducting chemistry experiments”: Mid (undecided), post (somewhat confident). Explain why your perceptions changed.

M35: Probably “somewhat” because of the nanotechnology labs, because before I hadn't had experience designing a procedure for my experiments, and then afterwards we had two labs that we had to design the procedure for the nanotechnology labs, so I felt that helped with determining like how to procedure-wise design an experiment.

R: (Confidence undertaking experimental tasks) 2C— “Designing and conducting chemistry experiments”: Mid (undecided), post (somewhat confident). Could you explain this change?

M41: It had to do with the discussions we did and how the TA didn't give us procedure during the discussion process, because he wanted us to create it our own, so I felt more confident because I did the procedure and when he explained it was correct. I was more happy that I managed to be able to do that. The discussion really helped in designing the procedure.

R: (Confidence) 2C— “Designing and conducting a chemistry experiment”: Mid (somewhat unconfident), post (totally confident). Explain why your perceptions changed.

M65: I think at the beginning I wasn't quite sure because we never had to do that, but when we were given a topic towards the end [Nanoscale science concepts] and go “design your own experiment for this or figure out what you have to do, and then I was like “oh I can do this.” You know, I was more confident because I have actually done it.

Nevertheless, the findings revealed that two students (M05 and M55) felt that they improved on their confidence towards these tasks due to the *prolonged laboratory experience*. They stated that exposure to many experiences made them feel confident in designing and conducting the experiments without supervision.

R: (Confidence undertaking the experimental task) 2C— “Designing and conducting a chemistry experiment”: Mid (not at all confident), Post (somewhat confident). Please explain this change.

M05: I think it's of course going from the start of the lab to the end of the lab, and it's just like now I have all this kind of experience and I can kind do it now.

R: (Confidence) 2C— “Designing and conducting a chemistry experiment”: Mid (undecided), post (somewhat confident). Please explain why your attitude changed.

M55: I think just the experience we had in the lab with being able to do it in the lab a couple times helped me become more confident in conducting experiments.

Another factor attributed to the improved confidence in these tasks was *group learning* (an element of the inquiry approach), which was expressed by participant M31. Although a junior and chemistry major, M31 had no prior experiences with group learning, as well as designing experimental procedures. However, exposure to the nanoscale science-based experiments made him realize the value of group learning. He also pointed out that prior to the nanoscale science-based experiments where he got to design the experiments, he held the belief that experimental procedures have to be developed by experts, and tweaked if changes have to be made. The nanotechnology experiments, however, gave him a first-hand experience to develop experimental procedures like expert chemists do. See the interview excerpt below:

R: (Confidence2C— “Designing and conducting a chemistry experiment”: Mid (undecided), post (somewhat confident). Could you talk a little bit about that shift?

M31: I think before I sat down and did group project, I kind of thought that procedures were pretty mystical due to the fact that someone had written them down a long time ago and people just tweak them, but after doing the project I realized it's not as mystical as I thought it was. As a chemistry student, I think if I sat down and had a problem and was with a group we could make a lot of progress.

Reading the procedure and conducting the experiment without supervision—positive change. Follow-up results on this item indicated that *prolonged lab experience* and *nanotechnology experiments* influenced students' perception change. For instance, participant M42 expressed that she developed some confidence in reading a procedure and conducting experiments after she getting used to her lab partner. Given that the lab

requires students to work in pairs, M42 needed more lab experience to learn her partner, open up and be able to share ideas without feeling intimidated. Her success to communicate freely with her partner happened towards the end of the semester. Her explanation to the observed attitudinal change is provided below:

R: (Confidence in undertaking different tasks). “Reading the procedures of an experiment and conducting the experiment without supervision”: Mid (undecided), post (somewhat confident). Explain this change.

M42: For mid, I think I was still new in trying to see where I’m doing, and I haven’t known my partner that much, so we communicate but we don’t really communicate. In post, I know her more and we get along and we kind like divided parts, ok you do one I do two. I think that’s why it [perception] changed a little bit.

It is probable that the structure of the course affected this student’s social aspect. Generally, the design of the conventional experiments does not allow students opportunities to discuss their ideas with the partner. Rather, students come to the lab, collect data, and leave without getting a chance to share ideas on the observed phenomena. There is no doubt that if the labs reinforced group discussions, students would take short time to become familiar and open up with their peers. This can ultimately improve their confidence in undertaking laboratory tasks.

Nanotechnology experiments were perceived to be beneficial in improving students’ confidence in the task in question. For example, participant M56 highlighted that the less ‘cook-book’ nanoscale science experiment procedures forced her to think about the procedure with less guidance from the TA which, in turn, improved her confidence in executing the experimental tasks. See the interview excerpt below. Overall, the inquiry approach played a great role in improving the student’s confidence.

R: (Confidence) 2C— “Reading the procedure for an experiment and conducting the experiment without supervision”: Mid (somewhat confident), post (totally confident). Explain this change.

M56: I think going through the lab procedures that we did where it was less cook-book [nanoscale science-based experiments]; sometimes you had to know how to set up the experiment, and getting less feedback [guidance] from the TA compared to the previous labs gave me a little more confidence.

Determining what answer is required from a written description of a chemistry experiment—negative change. As previously discussed in Chapter 2, laboratory work plays an important role in equipping students with scientific and manipulative skills, among others. It is also important that students understand the scientific process, and be able to implement scientist-like practices to provide a solution to the problem being investigated in a laboratory setting. Results on students’ confidence in determining the solution to a written chemistry experiment showed that many students were less confident to do so towards the end of the semester (post survey). Out of the two participants interviewed on this item, one participant (M47) perceived that her *inexperience with complex chemical instrumentation* (e.g., GC) introduced towards the end of the semester was a major factor for the observed decreased confidence in undertaking this task.

R: Survey 1 (confidence in undertaking different tasks); “determining what the answer is required from a written description of a chemistry problem”: In mid, you felt totally confident (score = 5), but in the post you felt somewhat confident (score = 4). Could you explain that change?

M47: I think towards the end we started using instrumentation we were not used to, so I felt not confident in using the instrument like the GC, etc.

R: So was it the analytical techniques that were the problem?

M47: Yes

R: So were you introduced to GC in the lecture before coming to the lab?

M47: It might have been just a personal problem because the only chemistry class I took here before was general chemistry, which was titrating. A lot of instruments while I did learn a lot, I kind felt behind because it was presumed you knew how to use the equipment.

Understanding the operating principles of an analytical instrument is important for accurate data interpretation. If a student is challenged by the operation of the instrument, then it is difficult to come up with results, which are important in solving the problem of interest. The above scores show that M47 was very confident in the middle of the semester. Until this period, she could confidently determine an answer from an experiment using data from the instruments, because she had prior experience using these instruments. Her lack of experience with new chemical instrumentation was challenging.

Another factor for the decreased student confidence was *complex research questions* [inquiry approach] that students needed to investigate. For M65, she indicated that prior to the nanoscale science-based experiments; she could determine an answer for any experiment with much confidence. With nanoscale science-based experiments demanding student critical thinking in answering the questions being investigated, she was less confident in carrying out this task. Based on her explanation for this change (see excerpt below), she pointed out that the research questions included in the nanoscale science-based experiments were complex and difficult to comprehend. However, sharing ideas with her peers helped her in realizing that she could experimentally answer the questions, but with less confidence.

R: “Determining what answer I required from a written description of a chemistry problem”: Mid (totally confident), Post (somewhat confident). Could you explain that change?

M65: At the beginning I felt I could figure out that no matter whatever it’s asking I could figure it out. For the most part in my head, I’m usually able to figure stuff out. But then as labs went on I saw several questions and like “I have no idea what this is asking.” ... I think there was one question in one of the nanoscale science-based experiments that I was completely lost on what it was talking about, but when I asked in my group they told me the answers and like “oh, I know how to do that.” But there were several other labs that did the same thing like “I don’t know what you were asking.”

The observed decrease in confidence can be explained in the light of the instructional approaches employed in teaching this course. In conventional experiments, students are given directions of what procedure to follow, and the chemical instrumentation relevant for the experiment. They are also provided with information about the expected results. Therefore, getting results in these experiments require less effort on the part of student. The nanoscale science-based experiments, however, demanded high effort from the students; rather than the instructor. Students were provided with research questions in which they had to discuss with their peers on how to solve them, develop the procedure to investigate the problem, identify the relevant analytical techniques, as well as interpret the data with little guidance from the instructor. Consequently, they felt less confident to determine answers to experimental problems.

Confidence applying concepts learned to real-world experiences—negative change. Based on the two participants interviewed on this items, *contextual factors* (e.g., *student major and students’ competency in the learning*), and *novelty of the*

nanotechnology experiments, influenced some students' confidence in applying concepts learned in class to real-world. For instance, M05 explained that her major being biology, it was difficult to translate the chemistry principles she learned in this course to real-life experiences. She also pointed out that her incompetency in understanding the concepts in question, especially from the lecture class and inability to translate them into the lab contributed to the observed attitudinal change.

R: "Applying chemistry concepts learned to real world experiences". Mid (somewhat unconfident = score 4), post (undecided = 3). Please explain this change.

M05: I don't think this really comes from the lab, I think it comes from my struggling with the class (lecture)—[self-incompetency]

R: So do you mean whatever you learned in class didn't have relevance, or could you clarify that?

M05: I can't see where it applies even though he will tell us you know, if you work in a lab you will do a chromatography....coming from a field that's not a chemistry major, I'm like, "I'm not gonna use this". But it also comes not really picking up things in class that I should be, and not doing well as I should, you know. Not understanding and not being able to apply—[student major influence].

Lack of prior experiences with the nanoscale science concepts that were implemented (i.e., the novelty of nanoscale science concepts) was associated with participant M65's decreased confidence in applying the concepts to real-world problems. She explained that she had a good understanding of the concepts taught in conventional experiments because the concepts were general, and that she had previously learned most of them in other lab courses. Consequently, she felt totally confident in applying the learned concepts to real-world. However, her inexperience with nanotechnology concepts

decreased her confidence. Unlike the normal labs where she could directly relate the content real-world, she could only relate the nano concepts to real-world after looking up for information on nanotechnology. Overall, M65's prior knowledge on the concepts influenced her confidence in applying the concepts to real-world.

R: "Applying the chemistry concept learned to real-world experiences." Mid (totally confident), Post (somewhat confident). Please explain this change.

M65: I think the gold nanoparticles actually changed that one because like for the first labs [normal labs] I knew what the concept was, and I was like I can relate that. When I had the gold nanoparticle, which is something I hadn't seen I was like I don't need to know how to do that information. Like I had to do more research and look into it to be able to understand how that was even related.

R: What helped you to relate those concepts in normal labs to real-world experience?

M65: I think those were pretty general concepts, and for most of them it gave you the description and like "here is what is used in real-world" and I can think even though the nano particles did [have relevance], I did not make the connection. I think for the most part I had done the lab concepts in other labs and talk like "this is where you could use this in somewhere else" whereas for nanotechnology we hadn't done that.

Theme 3: Interpretation of the Quantitative Results: Reasons/Factors for the Observed Perception and/or Attitudinal Change in Inquiry Learning Environment

Results on inquiry learning showed statistically significant mean difference between the post and the mid scores. Significant improvements were noted in the post, and focused on perceptions and/or attitudes towards the activities, the instructional approach, teamwork, ownership in the learning, and ability to apply the learned concepts. Discussion of results in this section will mainly focus on the factors that led to observed

significant change in perceptions or attitudes, as well as general discussions on the negative and positive changes.

Perceptions about the Laboratory Activities

Relevance of activities to real-world experiences—significant change.

Although students indicated less confidence in applying the concepts learned in the class to real-world problems (previously discussed) towards the end of the semester, results showed that their perceptions about the relevance of the activities to real-world experiences were higher in the post than in the mid survey. Follow-up interviews revealed that nanotechnology experiments were the main factor for the observed perception change. In particular, the interview participants highlighted the nanoscale science experiment #2 as the main cause of their perception. Like some participants who felt that identifying and determining pesticides in the vegetable leaf was relevant to their daily lives (e.g., open-ended survey responses), participant M42 felt that the nanoscience implemented lab was the most relevant because she eats lettuce daily, and therefore determining the concentration of the pesticide in the vegetable was more relevant to her. When asked why she changed her perception from “neutral” (mid) to “Agree” (post), she said: *“Because we did activities like finding concentrations of pesticides; I eat lettuce every day in my life, so it’s more relevant to me.”*

Similarly, participant M52 felt that the content of the nanoscale experiment #2 was very relevant to him not only because he could directly relate the experiment to daily life, but he also used analytical techniques he previously learned to solve the research problem. See the interview excerpt below.

R: (Survey 2: Inquiry-based): “I found the activities relevant to real-world experiences.” Mid (neutral), Post (agree). Please explain this change.

M52: So that was the pesticide experiment.... When we did the pesticide experiment I had a very solid goal that was clearly a real-world experience, and I was able to use techniques I have used in the past labs and applied that to something that I saw had a real-world experience.... The content was really cool with the pesticide one; that had a very like “oh, this is how it’s used in real life”, and that was really nice.

Reasons for non-significant positive and negative perception change.

Interview findings also indicated that *nanotechnology experiments* highly influenced the observed positive change in perception about the activities. In particular, students felt that these nanoscale science-based experiments helped them “*discover what they were expected of as learners*”. For example, M65 explained that the questions to be investigated in the nanoscale science-based experiments were more in-depth, and forced them to think about how they could go about answering these questions. He said

R: (Survey 2: Inquiry-based): “These activities helped me to discover was expected of me as a learner I have found.” Mid (neutral), Post (agree). Explain this change.

M65: I mean as the labs got further a long especially the gold nanoparticles, the questions that you have to answer for your lab report where more in-depth so it kind made me figure out “oh this is what you need to do in the lab in order to be able to answer those questions.”

Although follow up interviews were not done on the two items showing non-significant changes in perception, the observed perception on the item: “*these activities helped me to develop my team working skills*” may have been due to the limited experience in sharing ideas with a larger number of peers as well as not assigning

individual members group roles. In the mid, students knew their roles when working in pairs. When working in pairs, students are able to agree who should play what role. One may take the role of recording the data, while the other runs the experiment. Therefore, exposure to group learning in only two labs may not have been adequate to cause students to develop team working skills. Same reasons may apply for the observed negative change on “perceptions and attitudes towards teamwork” in which in the post, students felt that: *“the group worked less well as a team”*; *the group worked less well to overcome difficulties or problems they encountered*; and *“students could see limited ways in which they could contribute to a group task”*. However, one student indicated that the activities helped her develop team working skills. For instance, see the interview excerpt below:

R: “These activities helped me to develop my team working skills”. In mid, you agreed with the statement, and in the post you strongly agreed with the statement. Could you talk a little bit about that?

M47: In the mid survey, before then we have only worked with our group partners, that is 1 or two other people, and I was always used to working in the labs that way. So I did agree that it did help because I did learn how to manage like how to go about a lab. But afterwards, we all came together as a class and worked together. That helped a lot because I was able to work with a lot more people rather than just 1 or 2.

Students’ change in perception about their effort in completing the activities in the post (i.e., *“I felt I did not have to work hard to complete the activities”*; Mid = 3.36, Post = 3.15) is because they were challenged to design the nanoscale science-based experiments on their own; unlike in the normal labs where procedures were given. When participants were asked to describe their perceptions about the course during the

interviews, many felt that the normal experiments were standard and simple. They also explained that the experiments were similar to those found in other courses in terms of the structure (“well laid out procedures”), and did not involve a lot of thought process like the nanoscale science-based experiments. Others expressed the concern that they only need to show up to the lab, collect data, and go home. Examples of interview excerpts are provided below:

R: What is your general view about the normal lab experiments that you were exposed to in this course, that is, the non-nanotechnology-based?

M01: They seemed pretty much standard to me. If you needed to research something about the lab before you did it, it was pretty easy to just google search the title of the lab and find quite a few literature articles there other universities that had published methods for the lab online. So from that I gathered that you know it is pretty standard analytical methods that are used across the U.S.

M04: Pretty standard recipe based experiments... there's not a whole of thought involved in it. I mean, pretty much you go through step by step and complete it which is frustrating because its...with all that laid out there is really nothing to learn.

M05: I guess they were kind the routine, you know, familiar. I don't know if this really makes sense, but, you know, they are kind like all other labs; I kind know what to do; write pre-lab and kind enjoy doing labs.

M09: They were typical is what I would think. They are a lot more similar to other previous labs that I have taken and it's just based on how well you can read either data, or read things in the lab like a volumetric flask. Reading a meniscus in a burette, and it's not the most interesting to me, but it's still... I understand why you need it because that's the base for the rest of everything that you may need.

M18: For normal labs, we didn't have them like the nano units were written, you know, goals, questions to ponder. The other labs [normal experiments] were probably 15 -20 min on what needs to be done, we do the experiment, go home, write the lab report and turn it in.

M20: That they didn't have that, that they were just pretty much written out, like straightforward they were not really like, if you think about this then you know, or what would happen if maybe, you would do this or they really didn't get you to thinking much while you were doing the experiment it was more of afterwards like once you got your results.

M41: I guess that one was kind of give and take, so you just come, do it and that's it. And for me, because we are just students we just want something that we do, finish it and go home.... We just do what the procedure says and finish, then go home.

M55: They were pretty easy I thought. I don't think they were anything too hard at all. It was all kind the stuff I have seen before, so they were pretty easy.

Furthermore, interview findings on the general perceptions about the laboratory course in question indicated that a few participants perceived nanotechnology experiments to be difficult. For example, M42 felt that the nanotechnology experiments were challenging because there was no step-by-step procedure given for the experiment. See the excerpt below:

R: "I felt I needed to work hard to complete the activities". Mid (neutral), post (agreed). Explain this change.

M42: Because the last one it was about the nanoparticles and it was hard to understand it.

R: So, what was hard about the nanoparticle experiments?

M42: The equipment was hard to understand... It's not like step 1, 2, 3 [well outlined procedure].

Perception Change about the Instructional Approach

Instructor gave students the support they needed in the activities—significant change. Follow up interviews on the general perceptions about the lab course revealed that all the participants applauded the TA for his effective teaching. They felt that the TA taught well, and gave them the support they needed to learn. This may be the explanation for the observed significant and positive change in perception related to the instructor support. Examples of excerpts supporting this claim are presented below:

M01: The TA we had did a great job of teaching us and later in the lab, so that helped increase my experience as the semester went on, especially with regards to following methods sometimes the methods were unclear; the literature wasn't written very well and he kind of got us through there, modified it so that there was simple to understand.

M05: The TA was a wonderful teacher and for the most part the directions worked really well; if they didn't, he did great sorting that out and I think that's a big part of it. It was a lab.

M15: It helped that the TA was awesome. He would always be there for you to help you a lot and guide throughout. He didn't like give us the answer, he actually pushed us to think like in the last labs he pushed us to think critically about "oh, how does this data relate to what we are trying to find". It was really fun; I enjoyed.

M20: I feel like I had a really good, you know the instructor who was there to help and clear up anything I needed help on.

M56: I thought the TA was wonderful. He is probably the best TA I have had in my undergraduate so far.

The classroom observations also indicated that the TA successfully implemented inquiry as expected. He provided students with the big questions to discuss, and encouraged them to come up with a procedure to answer the experimental questions. Furthermore, he frequently probed for students' ideas, and challenged them to think. Overall, the TA was a guide in the learning; rather than a transmitter of information.

Opportunities to establish research questions—a positive significant change.

Although follow up interviews were not done on this particular item, it is obvious that students' perception scores on this item significantly improved after introduction to the nanotechnology labs. In the mid, students' perceptions were negative (Mean < 3), in the post the mean was slightly above 3 (i.e., Mean = 3.37). One explanation for the negative mean score in the mid survey is the 'cook-book' structure of the experiments and the expository instructional approach used—students are not given opportunities to think critically since all the information is provided to them, including the expected results. Interest is more on the product of learning (accurate numerical value), than the process of learning. Thus, opportunities to come up with research questions based on the data they collect are limited. The reason for the significant increase in mean score noted in the post is due to the exposure to the nanotechnology experiments. These experiments required students to critically think, question their observations, and find answers to their questions. This, in turn, promoted better understanding. For example, M52 said:

“nanoparticle experiments were easier for me to understand, and I felt like the more I ask questions the more I participate [and] the more I learned.”

Attitudinal Change towards Teamwork: Reasons for Significant Changes

The significant changes noted on items under this category are due to the nanoscale science-based experiments in which students were afforded opportunities to work in groups of four individuals, rather than in pairs in normal labs. Following the nanoscale experiments, students strongly felt that *“the group was effective in developing shared goals”*, and that the *“team members were helpful in students’ learning”*. Most students appreciated working in large groups because they perceived to have helped them in understanding the concepts better (see discussion under general perceptions about the course: interpretation of the open-ended survey results).

Taking Ownership in the Learning: Reasons for the Observed Change

As the quantitative results indicated, students had positive perceptions about, and attitudes towards taking ownership in the learning following the nanoscale science-based experiments. Some students felt that they (1) were better able to find information from different sources (significant change), (2) were more confident in their ability to evaluate the information they have found, (3) take more responsibility for their own learning, (4) learned how to plan their learning, and (5) felt a sense of control over their learning. Their unfamiliarity with the nano concepts, the procedure for the nanoparticle synthesis and mechanism behind the synthesis of nanoparticles, and the application of

nanoparticles as sensors reinforced them to search for, and evaluate information; plan and prepare prior to the lab, and take more responsibility for, and control over their own learning. Findings also indicated that more lab experience helped one student to develop confidence in evaluated the information found. Moreover, the switch of student role with the instructor reinforced the above behaviors. Examples of excerpts illustrating the aforementioned perception changes are presented below:

1. Ability to find information from different sources

M01: Doing the research for the chemistry behind the reactions was what I really enjoyed and there wasn't a whole lot of that method for the standard labs [normal]; it was basically they give you maybe the chemical for the reactions, the equations for the reactions and the standard method [well outlined procedure] and then was up to you if you want to further research anything on it, whereas in the nanoscale science-based experiments there were thought provoking questions that in order to answer in your lab report you will have to do some research on the chemistry behind the reaction, and you need to be able to do that.

M04: I felt those units [nanoscale science-based experiments] you had to do a little more background information. You couldn't just do... like with the other labs [normal labs] you could do your prelab 15 minutes before lab and quickly write something down in your book and put some tables up you know you're pretty much copying over the exact same thing by putting it in words and laying it out, whereas with the nanotechnology experiments you had to find some answers.

M65: I think I liked that better because it let me go online and look at other labs that had a similar approach and go "oh, this is how I could do this, or this is how I could do this" and then I could have like a whole concept then I would be like "oh, this one works best for this lab."

2. *Confidence to better evaluate the information found*

R: "I'm better able to evaluate different sources of the information." Mid (neutral), Post (agree).

M65: I think it had to do with the gold nanoparticles. The labs that we had to come up with your own method; how to do something because it made me research; like it made me go online and like look up other labs and go "how do I do this."

R: "Confident in my ability to evaluate the information I have found." Mid (neutral), Post (Agreed).

M42: In post, I had more confidence because I felt like I was in the lab more and so I had more experience and also I got help with my TA and my lab partner so I know how to read my results and stuff, and then from the results I can I conclude about my results, so I have more experiences [lab experience] from that.

3. *Taking responsibility for "my own" learning*

R: (Survey 2: Inquiry-based): "I felt I had more responsibility for my own learning." Mid (neutral), Post (agree).

M55: Just getting experiences, being able to things on my own in the lab helped me develop confidence. I think the exposure to the nanoparticle labs.

4. *Confidence in establishing "my own" research questions*

R: (Survey 2: Inquiry-based): "I feel a sense of control over my own learning." Mid (neutral), Post (strongly agree).

M01: It's directly because of the nanoscale science-based experiments. I really hadn't had any experience with research before that. I hadn't researched here [referring to the mid] yet at all. But doing nanoscale science-based experiments made me realize that it's not that hard to research. That's the way chemistry is really done—is constant research and trying to improve on your techniques. So, once I had experienced to put my skills to work, then I could easily design my own experiments in the future.

5. *Felt a sense of control over "my" learning*

R: (Survey 2: Inquiry-based): “I feel a sense of control over my own learning.” Mid (neutral), Post (agree).

M52: It was the gold nanoparticle experiments because like when I’m doing experiments and I don’t know what I’m doing I don’t feel control over my learning because I’m just struggling to keep up. But with the nanoparticle experiments it was easier for me to understand and I felt like the more I ask questions the more I participate them more I learned and that helped build a sense of control.

Other examples of interview excerpts illustrating students’ perceptions about a sense of control over their learning due to nanoscale science-based experiments are presented below:

R: What did you like about the nanoscale science-based experiments?

M15: It let us have control over the experiments but it was late [at the end of the semester], and obviously see how things everything like interacted and so you had to think harder. Sometimes students are just lazy and like “I don’t know how this happens. It forces you to do more research to figure out; to realize “oh this is how it interacts. Not to be lazy but it is a little more work to do, but it is fun when you’re doing it.

M41.... it gave me a sense of, and experience of how you will be later on, you know. So it made me more confident in doing it on my own, and I think it pushed me out of the comfort zone; just doing whatever I can do and that’s it and not learning as much [referring to the normal labs], you know. But these experiments [nanoscale science-based experiments] pushed me out of my comfort zone and to be like how I do the experiments to be resilient; make sure I do it this way or try to think more about it.

6. *Planning learning*

M63: I needed to read prior to the lab and kind get a feel for what is going on, so that way I could also not only think of it myself, but discuss it with my lab group.

Perception/Attitudinal Change towards Understanding, Applying the Learned Concepts, and Communicating Results

As shown in Table 4.9, participants showed a change in perception scores on all the items based on the post scores, including the item, “There was a lot to learn”. It may be argued that the nanotechnology experiments, especially the inquiry approach, improved participants’ attitudes towards presenting findings, communicating findings, solving problems, understanding the learning process, and relating well with peers. In this section, I will discuss the reasons for the observed change in perception on the item “There was a lot to learn”, as well as the significantly observed attitudinal change on the item “I can apply the concepts I have learned in this lab course in solving environmental issues in society.”

There was a lot to learn. While the open-ended survey responses revealed that most students felt they learned the most from the nanotechnology, findings of the follow up interviews on their general perceptions about the course indicated that participants learned little from the normal experiments. When asked what they did not like about the normal experiments they indicated that they did not learn a lot from the experiments. Examples of excerpts are provided below:

R: What did you not like about the normal experiments?

M04: I really don’t feel like I learned a whole lot. I mean, outside of what we had already learned in lecture, there wasn’t anything new, or there wasn’t this light bulb that went on and said “ oh wow I get it....You really didn’t have to search for anything because it was all there.

M35: So those labs [normal experiments] just felt like I didn’t learn as much as I did from a few of the other labs [nanoscale science-based experiments].

M41: Most of the time I would feel like I couldn't understand as much because it felt like it was more about like the broad sense of the topic of the experiment, so I kind of just listened and then do whatever was in the procedure that was given to us.

The participants expressed a number of reasons on their perception about having learned little from the normal labs. First, they stated that the experiments lacked clear experimental goals, and there was no a rationale for why they had to carry out the experiments in the manner they did, as well as the underlying principles behind the observed phenomena. See excerpts below.

M04: We didn't really talk about any of the reasons why we were doing what we were doing, or the theory behind it or what was actually chemically or physically going on within the reactions.

M31: I think it's the way that the labs were setup. There was a little bit of an introduction but it was just follow these steps. If there were some side notes and reasoning, or why you would follow these steps, or a group discussion beforehand that would help to understand the actual experiment.

M41: ...for me the thing was just to come to the lab, do whatever steps in the procedure, finish the lab and that's it, and I didn't really find time to know why is it that I'm doing the experiment, and what goes behind the experiment as much.

Second, some participants felt that the normal experiments lacked relevance to real-world experiences, and/or in preparing them for future work experiences. For example, participant M41 stated that she could not translate the content of the normal experiments to the applications in chemical industries, or in her future job. Similarly, M47 felt that she did not understand the applications of the normal experiments in real-life.

M41: I didn't get as much because I'm not really learning anything. I guess I'm just doing it, but not really understanding the application of it. So I felt as a chemist I realized it would be hard for me to own it if I don't learn how to understand why I'm doing this experiment and how I can apply the data on when doing my job, you know... I mean I got the understanding of what the experimental topic is, but not much on how it is used in many chemical industries.

M47: I guess I didn't like how they seemed very... they didn't really talk about how it could be used [relevance to real-world]. The first lab it did have introduction and it talked about how the technique was used and what it was used for, but over the semester a lot of them did not have any of that.

Finally, some participants stated that they did not learn much from the normal experiments because some were redundant in terms of the techniques intended or the content of the lab (e.g., M65), and/or lacked creativity (M01). They explained that they had learned the concepts and/or techniques in other classes, and therefore gained very little from the course in question.

R: What did you not like about the normal lab experiments?

M65: Sometimes I think they were kind boring because we had already done a lot of the equipment-type stuff... Basically, a lot of it was like a review.... Most of the techniques were things that we have done in other labs like we weren't really learning until we went to actually write the lab reports.

M01: Probably the lack of creativity, where you were just expected to sit down with the method and do the work. Unlike being able to kind of tweak the chemistry, maybe use my knowledge to increase the accuracy of the lab or of the yield whatever we're

searching for if it is the level of detection. There was really no opportunity to do that in the standard [normal] labs.

Interview findings on the reasons for the perception that “participants learned little from the normal experiments” align well with students’ responses to the open-ended survey on the reasons for the least learned experiment. In particular, students expressed that they learned the least from the “Calibration of glassware” experiment, and titration experiments. Examples of open-ended survey responses illustrating these reasons are presented below:

Calibration of Glassware: Reasons (Open-ended Responses)

“This is general chemistry lab! This type of lab is timid.”

“It was more busy work to ease us into the lab than learning.”

“Not applicable to anything.”

“Wasn't that great. Sure, glassware B can be calibrated to glassware A, but I didn't learn a lot.”

“It was more busy work to ease us into the lab than learning.”

“There was very little chemistry behind the lab and the work was very tedious”

“The experiment didn't work.”

“A lot of the stuff we had gone over ago.”

“Already learned how to do a calibration and it was very time consuming.”

“It was so dull, and didn't really matter.”

Titration Experiments: Reasons (Open-ended Responses)

“Titrations were common and I learned about them in all of my classes.”

“Because it seemed to be repetitive and not much thought behind doing it.”

“Very tedious and stressful.”

“We do so many of them in general chem [chemistry]; it gets boring.”

“Because it seemed to be repetitive and not much thought behind doing it.”

“We did so many titrations; there wasn't much more to learn.”

Similar claims were also identified from the analysis of classroom videos and observation field-notes. For example, at the end of the Nanoscale science module #1 lesson, many participants expressed that they liked this experiment because it did not involve titration: *“I liked it [Nanoscale science experiment # 1] because it was not titration”* [Participant from Group 5; Source: Classroom observations].

In addition to the normal experiments, the observed change on the perception score for this item could also be attributed to nanotechnology experiments, even though only five participants felt they learned the least from the nanoscale science-based experiments. Reasons for the nanotechnology experiments varied among the five participants as revealed by the open-ended survey included: the disjointed nature of the two nanoscale science-based experiments (1 response), working in a large group, that is, four individuals per group (1 response), familiarity with the nanotechnology concepts (1 response), content not useful—use of equipment was the only useful technique (1 response), and lack of a procedure thus inadequate preparation for the lab (1 response).

Examples of excerpts:

Nanotechnology Experiments: Reasons (Open-ended Responses)

“This lab seemed very disjointed and was hard to keep up with when we stopped to work only to repeat it again.”

“The groups we worked were too large for the job; it made functioning and learning in the lab difficult.”

“It seemed the only new material that went well in the labs were the use of equipment.”

“What I learned I already knew.”

“Couldn't really prep for lab because we worked out the procedure.”

Ability to apply learned concepts in solving environmental issues—

significant change. Findings based on the interviews revealed that the nano-pesticide experiment positively influenced participants' confidence in applying the learned concepts to solve environmental issues. Nearly all the participants interviewed on this item indicated that following the normal experiments (mid), they did not see how they could apply the concepts learned in solving environmental issues. However, exposure to the second nano module gave them a first-hand experience with a real environmental issue (e.g., participant M31, M20, and M42), and helped them see how they could use their gold nanoparticles, and/or analytical techniques to identify and quantify the pesticides in the vegetable leaf they were supplied with during this lab lesson (e.g., participants M04 and M52). See examples of excerpts below:

R: “Applying the chemistry concepts learned in solving environmental issues”. Mid (agree), Post (strongly agree). Please explain this shift.

M31: I think I always felt that chemistry was important in better solving environmental issues and after we did the pesticide lab that was just more reinforcing of that and it showed that chemistry can indeed be used to solve environmental issues if used the right way.

R: “Applying the concepts the concepts learned to solving environmental issues”. Mid (Undecided), Post (strongly agree). Could you please explain this shift?

M20: Ok, I guess because with the environmental part I would say that we did an experiment with like pesticides and stuff like that.

R: "I can apply the concepts learned in the lab in solving environmental issues in the society". Mid (disagreed), Post (neutral). Could you please explain this shift?

M42: I didn't put agree because I'm still a student like I'm not really solving issues in the society; only big people [experts] do it. But I changed from disagree to neutral because in the later labs [nanoscale science-based experiments] it's more like a real issue, so that's why I changed my mind.

R: Survey # 2- item 42. "I could apply the concepts learned in this course to solving environmental issues". Mid (neutral), Post (agree). Could you please explain this shift?

M04: Definitely, seeing that you could apply quantitative analysis to solve environmental issues made me see the connections on how the analysis techniques and the concepts could be used to solve environmental issues, but before I didn't realize that. The nanoparticle labs were pretty interesting because that's pretty quick and easy method to find the presence of something [referring to the use of gold nanoparticle as sensors for pesticides]. I found that intriguing that you could do that really quick. And you could almost do take your bottle test kit out in a field, you know. I could envision being able to do something like, and look at the color change!

R: (Survey 2: Inquiry-based): "I can apply the concepts learned in this course in solving environmental issues in society." Mid (neutral), Post (agree). Could you please explain this shift?

M52: We talked a lot about the environmental issues in the lecture because the professor is involved in environmental issues. But I had not been able to apply it, so I was kind neutral in the mid. I figured there are environmental issues and maybe I can analyze them, but I was not sure I was told them. Once I actually got to analyze them in the lab—the environmental issues like pesticide on a cabbage leaf, I figured it would be easier for me to look at different types of pesticides, to what they affect, and I realized I can go a step towards solving the problems caused by them.

Moreover, the video clip on the “contamination of orange juice with pesticides” influenced the attitudinal change for participant M47. She felt that discussing the pros and cons of pesticide use, the role of chemists in detecting the concentrations of the pesticide, as well as her involvement in determining the amounts of pesticides in the vegetable leaf was a good platform in helping her see the application of the concepts in solving environmental issues.

R: “I can apply the concepts I have learned in this course to solving environmental issues in modern society.” Mid, (agreed), Post (strongly agreed) with the statement. Could you please explain this shift?

M47: Well that was directly from the pesticide lab because we did talk about the good things and bad things about pesticides. We also talked about the jobs that chemists have in detecting the amount type of pesticide that is in food that we import, so I felt that could be directly related to like environmental issues in determining how much pesticide we have and stuff like that.

Interestingly, M04 stated that although he learned the quantitative analysis techniques, he could not see the direct application of these techniques in solving environmental issue in the normal experiments (mid). Following exposure to the use of gold nanoparticles as pesticide sensor, he appreciated this method of detection for he felt it was fast and he could take the kit to a field for sample testing. Similarly, M52 expressed that although the professor teaching the corresponding lecture course often emphasized environmental issues in the lecture, she did not see how she could apply the concepts in solving issues related to environment in most of the normal experiments (mid), until she had a first-hand experience of applying the concepts and techniques to analyze actual pesticides in the lab. This raises a crucial implication that theoretical

concepts alone are fruitless in equipping students with scientific knowledge relevant in solving problems in real-world. There is a need to provide students at all levels with real-world objects/items related to applications of the concepts being taught to increase relevance, as well as promote understanding.

In summary, most students showed positive perceptions about, and attitudes towards the inquiry approach. One explanation of the drive towards the inquiry approach might be that most of the participants in this study were seniors and juniors who might be anticipating working in chemical industries, where they will be in control of their research responsibilities, and therefore, feel intrigued to take control over their own learning. For instance, one participant stated that *“I plan to work in the industry and these are the type of experiments that we will do”* (Source: Open-ended Survey Item 3b). This claim was also confirmed from the classroom observation field-notes—during the Nanoscale science module # 1, one student said to his group partners that *“This lab would be good if you were going to work in industry where you need to design experiments, know how to use equipment and analytical techniques, and collaborate with other members in the industry.”* (Source: Classroom observation field-notes and video).

Theme 4: Interpretation of Quantitative Results: Reasons for the Observed Change in Perceptions about the Course and Student Learning

The discussion of results in this section centers on the general perceptions of about the laboratory course in question based on findings of the survey instrument # 3 and the follow-up interviews. While results on perceptions about student learning strategies and indicators on when their learning occurs indicated a decrease and

improvement on some items, no follow-up interviews were made on these items.

However, future research work should strive to uncover the reasons for the observed change in perception. This information will be vital in restructuring curricula and instructional approaches to reflect strategies that can help students learn better, as well as improve their conceptual understanding.

Results on students' perceptions about the laboratory course in general (based on survey instrument # 3) indicated improvement on most items, except that "students felt that often times they did not understand the concept behind the lab experiments", and that "it was not clear how the experiments fitted in the course". The reasons for these observations can be related to the previously discussed reasons on why students felt "there was not a lot to learn". Such reasons may include: failure to provide students with information on the application or relevance of concepts and techniques to real-world experiences; not understanding the reasons for the design of the experiments (i.e., why follow the procedural steps in the manner they are laid out); lack of interest in the learning due to lack of novelty and creativity of the normal experiments (redundancy of the experiments).

Some participants indicated that "doing labs in this class was not like following a recipe in cook-book" following the nanotechnology labs. One explanation for this is due to exposure to inquiry approach they experienced in the two nanoscale science-based experiments, in which instead of following well outlined procedures; they designed the procedures on their own. However, the experience with designing of experiments was not long enough to warrant any significant change, as the normal labs were 4 times the number of the nanoscale science-based experiments (i.e., 2). The interview findings also

confirmed that they criticized the “cook-book” steps provided in the normal labs.

Examples of participants’ quotes are provided below:

R: What is your general view about the normal lab experiments, that is, the non-nanotechnology that you were exposed to in this course?

M04: Pretty standard... recipe-based experiments. I mean, pretty much you go through step-by-step and complete it which is frustrating because with all that laid out there you can’t get something out of it if you are the type of person to pry into why you are doing things.

M15: The normal labs got a little boring at times. It was just, you know, here are some chemicals and here is the instruction list, and go at it. So it’s like a recipe out of a book.

M41: I guess that first it was kind of just like following the procedures and we did just, you know, whatever the lab instructor explains.

Furthermore, some participants felt that “the lab manual was more well written (easy to understand)” in the post than in mid. Their perceptions were influenced by the nanoscale science-based experiments. Few participants felt that the nanoscale science-based experiments had (1) clear goals of the lessons, (2) had elaborate and in-depth introduction that helped students to see connections between the concepts they were learning in the classroom with their daily-life experiences, (3) helped students to understand why they were designing the procedures in the manner they did, and (4) helped them to think critically about the chemical instrumentation relevant for the experiments. For example, participant M18 said:

M18: It [nanotechnology experiments] is very well thought out. It flows, and I really like when things flows like the theory, goals..., because when the content is written really well, then you learn something. I can tell you more about nano particles than any of the

other experiments combined.... I really liked the nano the way they were laid out like theory; what's the main goal; breaking down by parts; goals; know you, you can't just get a big bite from the lab; you have to break it down so it's easier to comprehend and learn something. So if you are just going through it [as a whole], your blood pressure is going up and you're not learning anything, so it's a waste of time and money that you spend on this.

The observed significant change in perceptions on the items "I like labs that I get to design an experiment to answer a question" and "This course provided opportunities for me to help design experiments to answer a question" is directly related to students' exposure with the inquiry approach in the nanoscale science experiments. As previously highlighted, most students indicated that they had no prior experience with the inquiry approach, and therefore in the mid, they were neutral on whether or not they liked designing experiments. After experiencing the designing of experimental procedure on their own, they felt it was fun and/or exciting. For example, when asked to explain why her perception changed from neutral (mid) to agree (post) on her likeness to design an experiment, participant M15 stated that:

R: Survey # 3- item 9. "I like labs that I get to design an experiment to answer a question". Mid (neutral), Post (agree). Explain why you changed your perception.

M15: Initially I was never introduced to one. Initially it was just "ok, let's do this and that and it was the normal experiments were like a recipe. And I was actually introduced to one [after mid] where I was able to control it myself; where I actually got to help the group design what we gotta do. So then I decide, you know, "this is actually more fun; more engaging."

Analysis of the classroom observation field-notes and classroom videos revealed that a majority of students liked designing experimental procedures and the inquiry approach in general. For example, when asked the TA to express their experiences with the Nanoscale science experiment # 1, they said:

TA: *What is your feel about the experiment [Nanoscale science experiment # 1]?*

Group 1: *"I like the idea that we were able to design the procedure."*

Group 3: *"I like it that we were able to discuss in groups and come up with ideas.... I actually do not like the procedures we are given, it makes it boring. I think this lab was interesting and we should be doing that."*

Group 4: *"I like that we had prompts that helped us think and make sense of the lab."*

Group 5: *"We had to think a lot" [in designing the experiment].*

Furthermore, findings on the follow up interviews confirmed that participants were excited about designing the experiments on their own. They indicated that designing experiments was fun and exciting because it increased their confidence in doing the lab (e.g., M01), felt engaged in the learning (e.g., M15), and helped them develop research-based skills (e.g., M35). Examples of interview excerpts demonstrating these claims are provided below:

M55: I think that's pretty cool to be able to do that [design experiments]. It is kind nerve-breaking if you're no sure, but once you figure it out you feel pretty good about it; I liked doing that.

M01: I felt more confident than before doing those nanoscale science-based experiments in designing my own methods. And it kind gives you a sense of excitement where you step back and say "wow! I actually did this". There is a certain amount of pleasure at the end of the day when you realize that all that sitting in class for hours and hours and taking

tests actually does pay off in the end, and it helps you to design meaningful processes like this that could be used to help the rest of the world in the process.

M15: I just really enjoyed the experiments [nanoscale science-based experiments] where we did get to design ourselves. It was more engaging.

M35: I liked that we were able to in our group to determine our own experimental procedure, whereas in the other labs, the experimental procedure was just given to you. So I thought that it was helpful in developing like research-based skills.

Interpretation of the Open-ended Survey Results Using Qualitative Findings

Survey results showed that a majority of the participants (38%) indicated they learned the most from the nanotechnology experiments. Moreover, results indicated that the nanotechnology experiments were perceived to be the most relevant to students' daily-lives and/or modern society— with 69% of the participants ascribing the relevance of nanoscale science-based experiments. It is important to note that while the open-ended survey required students to indicate which “experiment they felt they learned the least from”, findings on this item have been integrated in the previous discussion of the structured survey responses, particularly on the students' perceptions on the item “There was a lot to learn” (i.e., under Theme 4). Therefore, reasons for students' perceptions about the “least experiment learned from” will not be revisited in this section. In this section, I discuss the reasons for the reported students' perceptions about the experiment learned the most from and the most relevant to students' daily life/real-world.

Triangulation of findings based on the open-ended survey responses, end-of-semester

interviews, and classroom observations has been included as needed to support researcher's claims about the findings.

Explanations on the Choice of Experiment Most Learned From

Three main constructs pertaining participants' reasons for the choice of nanotechnology-based experiments as the most favorable experiment(s) learned from were established: (1) *the instructional approach—inquiry learning and group discussion* (2) *the relevance of the experiments*, and (3) *the chemical instruments involved in these experiments*. A discussion of each construct is presented below.

Instructional approach construct: inquiry learning and group discussion.

Participants choice of nanotechnology-based labs as the “most experiment(s) learned from” was mainly influenced by the instructional approach, inquiry-based approach and group discussion, employed in teaching these experiments. Responses associated with this construct were the most dominant compared to the other two constructs— 13 out of 25 reasons provided by the participants based on the open-ended survey related to the instructional approach. Moreover, over 80% of the interviewees highlighted inquiry and/or group discussion as the main drive for understanding the nanotechnology experiments. Students claimed that the nanotechnology experiments provided them with opportunities to search for information and compile the results, devise experimental procedures with minimal guidance from the TA, and develop critical thinking skills. Examples of the participants' excerpts to demonstrate this construct are presented below.

Searching for information. Searching for information from different sources is a characteristic of the inquiry-approach (NRC, 1996). It reinforces learning by

helping students integrate ideas to understand concepts, as well expose them to scientific research relevant in advancing the society. Some participants highlighted that they enjoyed searching for information from other sources because it reinforced their understanding the chemical principles behind the laboratory activities, as well as possible procedures for the experiments. In particular, they stressed that nanotechnology experiments afforded them the opportunities to search for information. Examples of the excerpts illustrating this claim are provided below:

[Nanoscale science experiments]: “Had to find answers [search for information] and compile results/procedure.” (Source: Open-ended survey responses)

R: *Was any of the methods of instruction useful in helping you learn the concepts better? If so, which one? (Interview)*

M01: I ended up searching for publications that could be used to write your own method for the lab or come up with the way to analyze different analytes with nano particles that sort of thing. That as interesting to me I thought like that was challenging and I learned quite a bit more from these [nano] labs.

M18: I think another thing about the nano particle labs I was trying to research, going to the SciFinder and find articles that they talk about the same thing. The second nanoscale science experiment was the organophosphorus pesticide. The first one was quite easy. The second one was like to think about more. For the second one when we were asked to come up with a procedure, then I was like. Ok, let me see what I can find from the SciFinder, and there were like 15 articles done by a Chinese lab which none of them were available here at Western. I think I found obvious articles and I was trying to read through it to see if I can find something. But these two labs were the most engaging, like thinking through it. So I think I learned the most out of them [nanoscale science experiments].

Designing experiments. The participants felt that designing the experiments during the nanoscale science-based experiments helped them to think critically. Consequently, they understood the learning process, and why they had to devise the procedure in the manner they did. Some also expressed that discussing the concepts in the lab, and critically thinking about what they were doing, and why they were doing was useful in fostering their understanding, as well as compiling their results. Examples of participants' excerpts are provided below:

Examples of Open-ended Survey Responses

[Nanoscale science experiments]: "Because we were forced to brainstorm methods of synthesis and analyzation [of the nanoparticles], I felt better prepared to perform the lab and understand the process clearly."

[Nanoscale science experiments]: "Because discussing an experiment before doing it made my understanding more."

[Nanoscale science experiments]: "Because it involved me thinking outside the box and putting my outside knowledge to use."

[Nanoscale science experiments]: "Inquiry-based experiments; I had to think more critically."

[Nanoscale science experiments]: "They made me think and understand what I was doing more than the other labs [experiments]."

[Nanoscale science experiments]: "It gave us more to think about and we had to design our own experiment. This made us understand the concepts better because there was more critical thinking."

[Nanoscale science experiments]: “Because we actually had to think about what to do in the experiment.”

[Nanoscale science experiments]: “We had to devise our way to do the lab procedure [for Nanoscale science experiments]; rather than just follow a procedure.”

[Nanoscale science experiments]: “I got to walk through why we did what we did.”

Examples of Interview Excerpts

R: Describe your experiences in learning through the inquiry-based approach, where you were given opportunities to design procedures.

M01: ...It makes you feel like you are actually grasping something instead of just doing some learning trying to get an A in the lab that kind of a thing.

M20: I really liked it because I would actually understand what it was that I was actually doing and understand what it is that I was actually looking for and the concepts and everything, not just after the experiment was over, but while I was actually at that point and I could think like, Oh well now I know exactly why you would do this and why you would do that, or you know what would happen if you did this, so, I really liked that yes.

M04: The exploration and the fact that you left there, understanding what went on...it actually makes your lab report easier to write because you actually do understand it, so you're not looking for stuff to fill spots or connections to draw that may not actually exist, or fancy words to put in so that your instructor will look at it and think that you put time into it.

M31: We worked in small groups to develop an idea like why would we want to make a procedure in a certain order. I thought that was really interesting and helpful because it helped us understand better because instead of just reading “this is how you do it”, that helped us understand....That was helpful.

M35: I thought it [inquiry approach] made me learn the material better than if I was just handed the instructions that said run the reaction or whatever. So I thought the kind of discussion that was incorporated in the lab helped solidify the understanding of what we were doing in the lab... I thought that approach [inquiry] was better for my learning and my understanding, and I also found that it helped me when I went to do the lab write up later that week, because I didn't have to look things up as much. I felt like I understood and I remembered that more because we had that discussion.

M41: It [inquiry approach] definitely helped me understand better, and helped me question more of these experiments. The previous one [traditional method] was fine, but we don't really take the extra effort to learn more about why we are doing it.

M52: I really liked inquiry-based labs because it's less like following a recipe and less like going towards it and more actually learning the material in the lab. It connects lab better to the class and actually you're learning the material in lab instead of just following a recipe and doing something in the lab.

M54: Designing the experiment helped me learn the concepts better because we had to design the experiment; we had think about what we were really looking at, and the best way to get the results.

Other participants felt that discussing in group was the best teaching method because it helped them understand the concepts better than the expository method. For example, when asked to state which method of instruction was better in helping them learn the concepts better, participants M47 and M52 said:

R: Was any of the methods of instruction useful in helping you learn the concepts better? If so, which one?

M47: The group discussions, because everyone had their input and I got more insights than just what the TA told us; what the concept was about; the way everyone was able to

collaborate and think of various answers. M52: Having us break into groups, discussing like why something would happen and then coming back and talking about the actuality was very helpful for my learning. Because for the most part I'm just told this will happen, and with these nanoscale science-based experiments I had to tell someone why it will happen.

Moreover, two participants pointed out that inquiry-based approach was useful in helping them retain the learned concept due to the practical experience involved in investigating and solving the problem. For example, M52 and M42 said:

M52: It [inquiry approach] is definitely the approach I prefer when learning. It makes the information easier to retain, because if I'm not just given something to memorize; if I go to find it out myself I'm more likely to remember it and I'm able to do a similar situation later.

M42: ...It sticks in my head like what steps should I do and why I do that because the TA kind like asked a lot of questions; what to do to have more concentration of pesticide so it made me think a little bit more and when I came up with an answer, it stuck in my head; it is more useful that way.

Content relevance construct. Relevance of the concepts to students' daily-lives and/or the modern world was the second prevalent reason for the choice of Nanoscale science experiments as "the most learned from". Participants pointed out that they learned the most from the nanoscale science-based experiments, because they could relate the content to their daily-lives, and that the content was applicable to their field of study. Seven out of 25 open-ended survey responses related to this

construct. Examples of excerpts from the open-ended survey responses are presented below:

Examples of Open-ended Survey Responses

[Nanoscale science experiments]: “It was the one that really intrigued me and had sufficient matter [content] that was applicable to my field of study.”

[Nanoscale science experiments]: “Because it applied to real-world problems that I would see while working.”

[Nanoscale science experiments]: “I learned the most from this lab [nanoparticle-pesticide sensor experiment] because I could directly apply it to real life.”

[Nanoscale science experiments]: “Because the concept was quite interesting” (2 responses).

[Nanoscale science experiments]: “I understand why we were designing the procedure in a certain fashion; what was going on, and how it is related to the real-world.”

[Nanoscale science experiments]: “The beginning of the lab was very informative and got me thinking about gold nanoparticles.”

Furthermore, interview findings revealed that some participants felt that the nanotechnology content helped them in interpreting data output from the chemical instrumentation associated with these lessons (M01 and M04), the application of nanotechnology in making biosensors (e.g., M15), and other real-life applications (e.g., M54). For instance, participant M04 stated that even though he was an undergraduate TA for a general chemistry laboratory course in which he used spectrophotometers in teaching on of the concepts, he did not understand how to interpret data using this equipment. However, exposure to gold nanoparticles as invisible solid particles helped

him in understanding the concepts of transmittance and absorbance in the quantitative lab course in question. Similarly, M01 indicated that exposure to gold nanoparticle; especially the change in colors of the solutions helped him understand how the UV-Vis spectrophotometers work. He indicated that he would apply the knowledge about the UV-visible spectrometry in his summer internship projects—see interview excerpts below.

Examples of Interview Excerpts

M04: Now I understand what kind of reading I was getting [from the spectrophotometers]. I understand more clearly. I was a TA for general chemistry and we did an experiment in Gen Chem II with spectrophotometer and I couldn't answer the question as to what the percent transmission was and how they related to absorbance. But now I can actually understand, like for nanoparticle now it's not like a bigger molecule that you can actually see. So you then you start, I think, in your mind goes from molecules that I can't see to spheres so as soon as you get that concept of spheres blocking the light then immediately you kind of realize what is going on in there.

M01: Definitely getting an idea of how to use different equipment it ended with the UV-visible because I know for me in particular I will be doing internship in this summer and using some of this exact machine and just having an understanding of how nanoparticles work because it's like, you know, that the color changes, but I did understand why, so that's was really interesting.

M15: We got to learn how nanotechnology was used for detecting pesticide and stuff like that; analyzing the concentrations of it I thought that was very interesting....It made us think critically about the procedure, which chemicals to add [roles of the reagents supplied].

M54: This is one of my favorite labs I have taken, because I feel like instead of just going into the lab and doing what you're supposed to do and leaving you actually learn more, especially with the nanotechnology. I learned how they are actually applied in daily-life and not just some test-tubes in class this semester round and getting the results.

Analysis of the classroom observation field-notes also indicated that participants enjoyed the nanotechnology-chemistry concepts, especially in synthesizing the gold nanoparticles and/or in using the particles as sensors for detection of organophosphorus pesticides. For instance, in sharing with her peers, one student said: *"I think this is very cool to see how it [gold ions] is changing from yellow to red."* Additionally, when asked by the TA about their experiences with the nanoscale science-based experiments, one group of students in fall 2013 semester said: *"We liked the concept of nanotechnology."*

Chemical instrumentation construct. The use of chemical instrumentation during the Nanoscale science experiments was the third main reason for participants' perceptions that these experiments promoted their conceptual understanding. Five of 25 responses from open-ended survey responses aligned with this construct. The wide array of instruments used in these two experiments in comparison to the conventional labs triggered participants' choice of the nanotechnology-based experiments as the most experiment learned from. In Nanoscale science experiments, students used single-beam UV-Visible spectrophotometers in which they were able to measure absorbance of their nanoparticles-pesticide solutions by scanning the wavelengths, instead of setting the nanoparticle solutions at specific wavelengths using simple spectrophotometer-20s. They were also exposed to the Gas Chromatography instrument where they discussed why and how they could use the equipment in lesson. Additionally, they were exposed to other

devices such as micropipettes in which they could accurately measure small quantities of their sample—a new skill that they did not get in the normal labs. The manifestation of this construct based on participants’ excerpts from the open-ended survey responses is demonstrated below:

Examples of Open-ended Survey Responses

[Nanoscale science experiments]: “The wide use of modern equipment (GC, micropipettes, and UV-Vis) was helpful.”

[Nanoscale science experiments]: “I understood how to work with UV-Vis spectrophotometers, GC. I understood % transmission versus absorbance relationship.”

[Nanoscale science experiments]: “I chose this lab [nanotechnology] because I used equipment that I’ve never seen before.”

[Nanoscale science experiments]: “Because I could experiment running [operating] machines.”

Interview findings also confirmed the manifestation of this construct. For instance, student M01 felt that nanoscale science-based experiments involved the use of a wide array of equipment and instrumentation that helped him in understanding the concepts and principles behind the operation of the equipment. He said:

M01: The instrumentation that we used was nice. We brought out to use some micro pipets for the nanoscale science-based experiments. We used gas chromatography and I did a lot of research with gas chromatography, UV-Vis analysis and mass spectrometry analyses specifically for the nanoscale science-based experiments, especially when we were doing the pesticide determination. And that was quite interesting.... I did a lot of reading for GC and UV-Vis analysis and mass spectrometry, and I feel like I understand those methods of analyzation quite a bit better now because of that [nanoscale science-based experiments].

Explanations on the Choice of Experiment Most Relevant to Students' Daily-Lives and/or Society

Common reasons for the choice of nanoscale science-based experiments related to *direct application to real-world, content relevance to chemistry/chemist-related industry/job, and novelty of the nanotechnology concept*. The manifestation of these sub-themes is presented below.

Direct application to real-world and/or everyday-life. A plurality of participants (13 out of 32 responses in open-ended survey) felt that the content and techniques learned from the Nanoscale science experiments directly applied to their daily-experiences, and/or in enhancing advancements in society, including solving challenging issues. Same reasons were also evident in the interview findings. Examples of some excerpts reflecting this claim are presented below:

Examples of Open-ended Survey Responses

[Nanoscale science experiments]: "Because it related to my daily life It applied to the lunch I ate today and I liked that."

[Nanoscale science experiments]: "It [pesticide contamination] is a concern that we hear and we eat food with it."

[Nanoscale science experiments]: "We were able to see what is on the food we ingest."

[Nanoscale science experiments]: "We used a real-world piece of cabbage in our experiment and analyzed our results."

[Nanoscale science experiments]: "Applied to real life situations."

[Nanoscale science experiments]: "It relates to agricultural issues."

[Nanoscale science experiments]: "I could see the importance to society in trying to determine the pesticide. From this you can remove the pesticide and learn the effects it can have on society."

[Nanoscale science experiments]: “I can see how it is useful environmentally speaking.

[Nanoscale science experiments]: “Because it related to the world of pesticides.”

[Nanoscale science experiments]: “They related to pesticides, which is a real problem.”

[Nanoscale science experiments]: “Because there was a lot of questions to answer that got me thinking about the actual science and [and] real life situations behind it.”

Examples of Interview Excerpts

R: Describe your experiences with the nanotechnology units that you were introduced to.

M04: The nanotechnology [experiments] were more [of a] scaled down version of what you would face in a real research condition.

M09: I liked the gold nanoparticle lab, and the pesticide lab. I liked these ones a lot because they really talked about real-world situations. It's not just about ok we made an aluminum or nickel compound, they have a real world application to me and made it interesting.

M15: They [Nanotechnology experiments] just made you think critically and kind relate it to the real-world a little bit better because it gave us a little better background to what we are actually doing, so that helps. The normal ones [experiments] were like “ok this is helpful because bla bla bla” and I'm like “um it didn't really make sense how they related to the real-world”. And for nanotechnology you could see “oh you know this is actually important what we are doing; what we are trying to find out”.

M52: The content was really cool with the pesticide one; that had a very like “oh, this is how it's used in real life”, and that was really nice.

Content relevance to chemistry/chemist-related industry. Some participants indicated in the open-ended survey responses that they learned the most from the nanoscale science-based experiments, because the content reflected the work done in

chemistry-based research (e.g., M01, M31, and M56), industry (e.g., M56), or their interests in future jobs (e.g., M41, M56). They pointed out that the activities provided them with experiences and skills that aligned with what chemists do, or what they will be doing in their future jobs. The following example excerpts indicate the manifestation of this claim.

Examples of Open-ended Survey Responses

[For nanoscale science-based experiments] “I feel I had to work the hardest and it helped me figure out what chemists actually do daily.”

[Nanoscale science-based experiments]: “Because we were asked to research methods of completing the lab, the process felt more related to real-world experience. In a lab, you must be able to think critically to design, improve, and run an experiment.”

[Nanoscale science-based experiments]: “It allowed us to use a variety of chemical instrumentation that is very useful in all aspects of chemistry in developing lab skills.”

[Nanoscale science-based experiments]: “This experiment [nano-pesticide experiment] helped me see the relevance of chemistry to modern society because it brought in a real world issue and used chemistry to evaluate the problem.”

[Nanoscale science-based experiments]: “Because it [pesticide contamination] is something chemists are trying to figure out, because it is a problem in society.”

Examples of Interview Excerpts

R: Describe your experiences with the nanotechnology units that you were introduced to.

M01: I felt like right off the bat even before we have done the lab; I was excited looking forward to the lab because this is something that is widely researched all over the world and still relatively needed in the chemistry industry.

M31: I liked especially the second nano unit because it had extremely relevant questions like pesticide use and how it affects our modern society. I liked that and felt I was doing something relevant in chemistry using fairly simple laboratory techniques.

M41: I really liked it [nanoscale science-based experiments], because it was also related to what I was learning in classes about nanotechnology: absorption and all these things. Yeah, I enjoyed it and I think it will help me later on in the future.

M56: I like, you know, you see in the news nanoparticles and nanotechnology you feel it's something being done in modern society today. I thought it was nice to feel like this is something being done in the real world today and this is a cutting-edge research some sort of we are doing something in the undergraduate lab that has direct relevance to what people are doing and in much higher in lab environments and in terms of what's being done in real-world industry. It's nice to kind get exposed to something that in a couple of years I might be working with the same; doing a very similar kind of work.

The interview findings also revealed that some participants regarded inquiry-based approach as the relevant strategy in helping them acquire scientific skills necessary in preparing them for the job market. They felt that this approach granted them the opportunity to experience scientist-like practices, as well as “real” scientific research skills they need in their careers. They showed dissatisfaction with the “cook-book” procedures they follow in the normal experiments.

R: Ok. Describe your perceptions about the inquiry-based learning approach, where you were given an opportunity to design your own experiment.

M01: It felt more realistic; we were doing a research and writing our own method; it felt like you are a real scientist instead of just like someone, a baker following a recipe for a lab. And that kind of gives you a sense of pride in your work; that you are the one responsible for finding the identity of a pesticide; that's something that an analytical lab would do on a daily basis.

M09: I liked it now that I'm used to it. It's better than the traditional: step 1 add this, step 2 add that... Because it's a lot more of a real-world and even when you read a scientific journal where somebody went through and said "I did this", you will not gonna read it in a step-wise format but in paragraph format.... I think it's a very important skill to have. I'm glad we did that.

M35: Overall, I really enjoyed the lab a little more because I thought like I somewhat helped design the actual experiment just because my group discussed the proper approach, which made me feel like it was a little more enjoyable. It gave me that sense of what I would do later in life like a research chemist.

M55: I really think that's kind cool trying to figure out [procedures] ourselves, because that's pretty much how we will have to do it towards the end... like when we actually have a job in the field or working in a university writing research; it's not like they will tell us what to do—we have to come up with our own methods to do things.

Novelty of nanotechnology concepts. A few participants felt that the nanotechnology concepts were novel ideas that provided them with knowledge about the advancements in modern society, for instance, in solving challenging issues. They indicated that the nano concepts provided insights into current advancements in modern society (1 response); nanoscience is relevance in addressing environmental and industry-

related issues (1 response); and [nanoparticles] can be used as biosensors for contaminants (2 responses). Examples of the participants' open-ended survey responses are presented below:

Examples of Open-ended Survey Responses

[Nanotechnology experiments]: "It gave an insight into things that are actually being done now."

[Nanotechnology experiments]: "[It provided insights into] "where nanoscience is headed and how each technique is used for environmental and industrial questions."

[Nanotechnology experiments]: "I learned it can be used for detection of chemicals [biosensors]."

[Nanotechnology experiments]: "Taught me about pesticide sensors."

In addition to demonstrating the relevance of nanotechnology to students' daily-lives, some interviewees highlighted that they enjoyed the nanotechnology experiments more than the normal experiments, because of the novelty of the concepts and/or field. A majority of the participants expressed that they had never had experience with nanotechnology research, and therefore experiencing it in the laboratory struck their curiosity and interest in the learning. Most importantly, a few participants felt that novelty of nanotechnology experiments helped them learn more in comparison to the normal experiments (e.g., M18 and M42).

Examples of Interview Excerpts

R: Describe your experiences with the nanotechnology units that you were introduced to.

M18: I can tell you more about nano particles than any of the other experiments combined.

R: Why is that?

M18: We talked with my peers... I also think it has to do with the novelty of nanotechnology. "Yes we are doing something new and exciting versus precipitating aluminum or precipitating nickel". It's like that's as old as the world! It's just like buying a new pair of shoes; you are excited, right; instead of having the same pairs of shoes. For me, the nanotechnology had the greatest impact.

M35: I enjoyed the nanotechnology aspect just because more and more nowadays you hear about nanotechnology, so I thought incorporating those into our actual quantitative experience in the lab was beneficial to me just because I guess it gave me like a first-hand experience into the technology that we are hearing about through our the world, so I thought it was helpful as students to get experience like actually first-hand making nanoparticles where you always hear about it, so it was cool for me to experience that; like I made nanoparticles today in the lab.

M42: It's new to me, so it made me curious; like how it works, how can I read the results you know kind thing. That's what I liked. It's new to me so kind liked new things, so just like it encouraged me to like learn more.

M55: I thought it was kind cool, because it was something that I hadn't seen before; it is something that I didn't have an idea about, so I actually did learn about nanotechnology I think that was interesting..... Exposing me to something that I have never seen in chemistry was kind cool.

M56: ...It was nice to feel like we were getting something not very old; something very new in the undergraduate lab work; that was nice.

M63: I think those labs [nano] were interesting in some way because it was something that we hadn't done before.

M41: I thought they [nanoscale science-based experiments] were really fun.... The introduction to nanotechnology was really interesting, and I never did nanotechnology previously in any of the other labs. This is the first time I read about it in articles or books and stuff....For experiments it helped me understand why we were doing it more and made the experiment more approachable and much more efficient to conduct.

Overall, a majority of participants felt that they learned the most from the Nanoscale science experiments, because of the inquiry-based approach embedded in these modules, the relevance of the content to students' daily-lives or to modern society, and the integration of a wide range of chemical instrumentations in one lesson. Nearly all the participants indicated that the Nanoscale science experiments were the most relevant to their daily experiences, and/or had direct application to society, chemistry research, or emulated the work of chemists. Embedding new and/or real-world contexts in science curricula can promote a better understanding of the scientific concepts by increasing student interest, engagement, confidence in the learning, as well as progression into advanced science courses and science-related careers. The interview findings of this study uncovered that some participant developed interest (M09 and M15) and confidence (M04), and felt more engaged in the learning (M09 and M15), and showed interest in nanotechnology research (e.g., M01 and M09) following exposure to the nanotechnology, a real-world context. The interview excerpts below verify these claims.

M09: I think I also enjoyed the second half of the labs [nanoscale science-based experiments] better because they are more interesting and they made me pay attention in

the lab better [engagement], if you will. Not to say that I'm a lazy student, but if it's something that you are interested in you will have a lot more interest of doing the lab and understanding the data as opposed to these are just numbers that don't really mean anything to me....It's nice to kind get exposed to something that in a couple of years I might be working with the same; doing a very similar kind of work.

M15: With the nanoscale science-based experiments, the instructor was more in-depth and he showed you videos and seeing how it related to the real-world, so you kind got the big picture idea better from the nano ones. That kind like got us more engaged and into the learning because we were like, you know, what we are doing is kind like important...It pushed you to get interested in. It was like a problem that you had to solve, like you a detective trying to solve and like "oh what I'm I going to do now to get this result"?

M04: I just felt like there is a confidence level build when dealing with real-world applications. It [nanoparticles] showed me that you could apply it to the stuff and see what's going on. ... Maybe take with you the theory because you understood well and you are walking around and look at something and say "wow! That will work right there; that piece would fit." So again relating to having or being involved directly rather than just doing something and being done with it.

M01: There is good possibility that if I were to get an industry job I would be doing research or work with nano particles. And I feel like that's beneficial to students altogether.

Overall, positive perceptions about the Nanoscale science experiments based on the participants' responses to the open-ended survey items, and classroom observation field-notes and videos were influenced by the content, the instructional approach (i.e.,

inquiry approach), the novelty of the nanotechnology concepts, and integration of a wide array of chemical instrumentation in one lesson—students appreciated the integration of more than one chemical instrument to analyze a sample. For example, the use of UV-visible spectrophotometer to identify the pesticides and GC to quantify the pesticide levels in the cabbage leaf, as well as the use of micropipettes to accurately measure small quantities of their samples spark positive perceptions about the course.

Working with items that have direct connections to daily-experiences (e.g., contaminated cabbage leaf and gold nanoparticles) also increased their appreciation of these experiments. Typically, ninety percent of the activities done in the conventional experiments offered in this course do not use items that students experience in daily-lives. Therefore, it is not surprising that an overwhelming number of participants' responses (69%) related to the relevance of the two Nanoscale science experiments over the conventional experiments.

Overall, many participants suggested the need to modify the structure of the normal experiments in the future course to foster deep conceptual understanding and retention of the concepts being taught; student critical thinking and engagement, and enhance student interest in the learning. They recommended that the normal experiments should be modified to include: (1) inquiry-lines of learning, (2) group and class discussions, (3) real-world situations or contexts that reflect daily-life experiences, and (4) integrate nanotechnology concepts into science laboratory courses.

Over 50% of the interviewed participants stressed that the recipe like procedure in the normal experiments should be scrapped and replaced with inquiry lines of learning where students can experience designing of experiments with minimal guidance, while

developing critical thinking skills and conceptual understanding. Some participants (e.g., M04) were critical about the overemphasis on the “accuracy of the numbers” placed in the lab course in question, and little focus on the process of learning the scientific concepts and the intended analytical techniques. Examples of participants’ excerpts illustrating the need to integrate the inquiry-based approach into the normal experiments in this course are presented below:

R: If you were the instructor for this course in the subsequent semesters, what changes do you think you make on all the experiments in general, whether the normal or nanoscale science experiments?

M15: Definitely much more of inquiry-guided instead of the normal labs that you really get didn’t as much out of it as when you’re consciously thinking about what you’re doing, so I will definitely put more of those like nanotechnology ones in there just kind like it makes you think more critically; makes you get more out of it; makes you be more engaged into it, so kind that.

M04: ...Have questions that are more based on what is going on [inquiry-based approach]; rather than “what’s your 95% confidence level”. I mean you do enough statistics all through science that’s even shouldn’t be there. One of the questions should have been more related to what happened to this or what will happen when you change this. From these questions, I had to google and start doing research to find out the answers. Through that process, I now understand it 100 times than I would if I did the calculations or turned in the graph and the summary conclusion, you know.

M01: I would probably modify the other experiments [normal] more like the nanotechnology labs and force the students that are in the section to do research before coming to the lab.

M20: Trying to not have them be laid out so much as a recipe cause that’s kind of how all of them were. Some of them were just like ok, do this, do that, do this, do that and then

you're done, collect your data and then you know leave. But I feel like maybe you should have like do this, and think why, and if you did this, then what would happen? I feel that they [faculty] should have a lot more of those labs [inquiry-based], or try to incorporate something like that into every single lab, even if it's not exactly how the nanoparticle experiments were laid out but kind of incorporate that more into each of the experiments.

M31: The inquiry approach promotes learning in a good way and if that can be applied to each lab that we did in a certain way I think that would be interesting.

M35: ...Incorporate the experimental design aspect in all the labs; like in the intro [introduction] like “how do you think this experiment should be designed”? And then have thoughts on that and give them [students] instructions or something.

M41: I think it [inquiry] is a very good approach. I definitely recommend it more in the future labs.

M47: I liked them [nanoscale science-based experiments]. I think maybe there could be more labs kind of structured like that and they should stay in the course.

M52: I would like to see to more often. It definitely makes learning easier for me. I guess I just like to see it more often but within the normal labs experiments so that I could use the inquiry approach which works better for me while learning the broader material of the course.

As previously discussed, participants in this study highlighted that group discussions were beneficial in reinforcing student thinking and understanding of concepts by sharing ideas, and learning from each. Two participants (M35 and M52) suggested that the instructional approach in future normal labs should be modified to incorporate

more group and classroom discussions, in which students will be given opportunities to share ideas with their peers during the lesson. Participant M52 emphasized that group/class discussions should be integrated in the entire lesson, that is, at the beginning of the lesson, during the activities, and at the end of lesson. They said:

M35: I would probably take a little more time at the beginning of each lab explaining, or having a discussion like we had in the nanoscale science-based experiments [at the beginning, during the activities, and at the end of the lesson]. So stuff like that really helped students in learning and remembering the material that was presented.

M52: ...Also, have discussions before the labs started. I really liked the discussion after the lab as finished also. So talk about lab before and after, and not just about the procedure but why we were doing it and what its application is.

Nevertheless, participants in this study demonstrated a strong interest in the integration of real-world situations or contexts into the course in question. Experience with nanotechnology and its application in modern society aroused their curiosity and interest for learning. When asked to explain how they could improve the experiments they were exposed to in this course, some participants (e.g., M15, M18, M04, among others) suggested the integration of real-world scenarios to show connections between the concepts being taught and every-day life experiences. They felt that the normal experiments they experienced lacked relevance in society, thus should be made more relevant.

Participant M18 stated that the emphasis on “accuracy and precision” was often boring, because there were no real-world situations in which she could see a direct application of the techniques or skills she was learning. She lamented that while

institutions are striving to prepare future workforce, there is a big discrepancy between the skills being offered in academia and what is actually needed in real-world. She asserted that experiments should be modified to reflect the skills students are required to develop from classrooms. Similarly, participant M04 felt that modifying the normal experiments to reflect current applications will help students develop interest and retention of the concepts. He highlighted that most students exposed to this course will remember the pesticide experiment more than the other normal experiments. Similar arguments pertaining explicit relevance of the normal experiments were also made by participant M15—see the excerpts below.

M18: They care about accuracy and precision and sometimes this can get boring. I'm sure there are experiments out there where you can measure accuracy and precision and still being more exciting, you know. To me the experiments were not that exciting. I would look for something to connect to the real-world because I'm like let's be realistic; academia and real-world there is a lot of discrepancy. There is this idea that we are being taught on how to think on our own, but also I will love to see experiments that are done in the labs reflect that, and what is done in the industry. I'm sure there are so many out there like treating of water.

M04: I think more of them should be related to current applications, because if you related it to current application or something like vegetable that we detail with in daily-basis, I think it draws the interest more for students working on them, and it sticks with them. I guarantee that any of the students in that class is gonna remember, especially the pesticide experiment, but they probably won't remember the other ones that we did. So I would institute more current applications.

M15: ... I just want more background to see is this relating to what we are doing in real-world. Not like "we gonna determine how much fluorine is I this", "today we gonna

determine how much aluminum is in this, I'm like "oh that is fun, but how it is relevant to the society?"

Finally, participant M20 indicated the need to integrate nanotechnology concepts more into to the science subjects, including chemistry. She said:

M20: I think that it [nanotechnology] is a very interesting subject and it's something that we should definitely in the science part of it, as chemists, look at it more. I thought it was pretty interesting, so it's something that I feel should be incorporated more into the labs.

Chapter Summary

In this chapter, the researcher has attempted to explain the quantitative results in the light of the qualitative findings. The major factors for the observed changes in perception and/or attitudinal scores between the mid and the post mean survey include: *the structure of the normal experiments; the structure of the nanotechnology experiments; prolonged laboratory experiences; and contextual factors—student major and competency in the learning.* The structure of the normal experiments, especially the cook-book procedures often influenced students' negative perceptions about chemistry, and the laboratory course. These perceptions were not only displayed in the mid survey, but also translated into the post, that is, after exposure to the nanotechnology experiments. Participants indicated that they learned very little from the recipe- type of the experiments offered in the normal labs, and that the experiments did not offer them opportunities to think critically, or engage in the learning. Furthermore, participants termed the normal experiments as "standard and simple", "boring due to "cook-book" procedures", "lacked creativity", and "less relevant to their daily-experiences or modern

society”. These negative descriptions played a big role in influencing students’ perceptions about chemistry, and the laboratory course in general.

The results showed that the structure of the nanotechnology experiments had significant improvement on students’ perceptions about, and/or attitudes towards chemistry, and the laboratory course in question. Nearly, all the significant changes reported in Chapter 4 were associated with students’ exposure to the nanotechnology experiments, even though prolonged laboratory experience played sometimes contributed to the observed changes in perceptions and/or attitudes. The influence due to the nanotechnology experiments were associated with the inquiry-based approach; the relevance of the nanoscale science-based experiments to real-world and/or students’ daily experiences, the novelty of the nano concepts, and the integration of a wide array of chemical instrumentation and equipment in the lessons. Results indicated that exposure to the inquiry approach influenced participants’ perceptions and attitudes in a number of ways, which include but not limited to:

1. Improved participants’ confidence in designing the experiments,
2. Improved confidence in establishing research questions that can be answered experimentally,
3. Improved interest in designing experimental procedures,
4. Participants’ appreciation of group learning,
5. Improved student ability to find, and evaluate information from different sources,
6. Improved interest in chemistry websites following the reinforcement to look for experimental designs, and relevant content to explain phenomena observed in the activities in writing lab reports,

7. Improved perceptions about the flexibility of chemists' ideas, and
8. Improved students' critical thinking skills.

The relevance of the nanotechnology-chemistry concepts to real-world positively impacted participants' ability to make connections between the content learned in the classrooms and their daily experiences. Results showed that they improved in their perceived abilities to solve environmental issues by applying the concepts they learn in classrooms. Additionally, participants perceived that real-world contexts were vital in arousing their interest in the learning, as well as ensuring the retention of the learned concepts. Many participants indicated that they learned the most from the nanoscale science-based experiments because of the real-world connection to the classroom content. Furthermore, the novelty of the nanotechnology improved students' curiosity and interest in the learning, as well as their perceptions about chemists. Finally, the integration of a wide range of chemical instrumentations and equipment in one lesson session fostered students' understanding of the complex analytical techniques such as GC and scanning UV-visible spectrometry, as well helped students to see the relevance and application of these techniques in solving real-world problems.

Although prolonged lab experiences was perceived as challenging, often times, it improved participants' perceptions about, and attitudes toward the course in question. For instance, some participants indicated that they developed confidence in reading a procedure and conducting experiments due to prolonged laboratory experiences with the experiments— meaning, the frequency of conducting experiments improved students' confidence in undertaking laboratory tasks. The results also showed that student major and self-competency in the learning contributed to one participant's perceptions about the

course. For instance, this participant felt that she could not apply the chemistry concepts learned in classroom to real-world because her major was not chemistry, but biology. She also felt that her inability to understand and transfer the concepts in the lecture to the lab influenced her ability to apply the learned concepts.

Overall, results showed that nanotechnology is a conduit for increasing student perceptions about, and attitudes towards chemistry and science, as well as enhancing progression into science-related careers. Many students felt that they learned the most from the nanotechnology labs than the normal labs. The nanoscale science-based experiments also elicited positive interest and confidence towards student learning. While the nanoscale science-based experiments were effective in improving students' perceptions and attitudes, students' laboratory scores for the two nanoscale science-based experiments were not significantly different from the laboratory scores of the normal experiments.

Limitations of the Study

The current study is faced by three main limitations. First, the sample size is limited— a total of fifty five participants ($n = 55$) completed the three surveys, even though the undergraduate student population of science majors in advanced levels (i.e., sophomore through senior), and enrolled in this course is usually small. Second, the intervention was based on only two Nanoscale science modules, which might be the reason for the few observed significant changes in student perceptions and attitudes, as well as the small effect size (i.e., Cohen's $d < 0.2$). A larger number of intervention experiments relative to the number of conventional experiments should be considered in

the future work to ascertain the effectiveness of the Nanoscale science experiments relative to the normal experiments. Finally, there was no control group to compare perception and attitudinal changes against the treatment group, thus causal statements cannot be made in generalizing the findings. However, the triangulation of qualitative data in explaining the quantitative results may qualify for the generalization of the findings reported in this study to a larger student population.

CHAPTER 6 : CONCLUSION, IMPLICATIONS FOR PRACTICE, AND FUTURE RESEARCH WORK

Conclusion

The goals of this dissertation project were to develop and implement two inquiry-based integrated nanotechnology-chemistry modules in the undergraduate quantitative analysis chemistry laboratory course, and evaluate the impact of the modules on science major students' perceptions about, and attitudes towards chemistry and the laboratory course in question. The objectives of the latter goal were to investigate the impact of Nanoscale science modules on students' perceptions and attitudes towards chemistry and quantitative analysis course; the underlying factors for the observed changes in attitudes or perceptions; and the students' perceptions and attitudes towards inquiry-based learning environment. In this section, I have summarized the results by revisiting each individual question that guided the study.

Question1: *How do undergraduate science majors perceive chemistry and science, and the quantitative analysis chemistry laboratory course?*

Findings indicate that science majors have positive perceptions (Mean > 4.0) about chemists, chemistry research, chemistry websites, and chemistry jobs, except on the item "chemistry jobs are challenging", in which students indicated a perception throughout the course that chemistry jobs are indeed challenging (Mean < 3). However, their perceptions about some of these areas decreased following exposure to the conventional/normal experiments. Significant negative changes were noted on the students' perception about "science documentaries being enjoyable", "chemistry jobs

being interesting”, and chemistry jobs being exciting”. Following exposure to the normal experiments, the students felt that *science documentaries were less enjoyable* (Pre = 5.50, Mid = 5.11, $\Delta\text{Mean} = -0.393$; $p = 0.030$); *chemistry jobs were less interesting* (Pre = 5.64, Mid = 5.30, $\Delta\text{Mean} = -0.339$; $p = 0.043$); and *chemistry jobs were less exciting* (Pre = 5.04, Mid = 4.57, $\Delta\text{Mean} = -0.464$; $p = 0.018$).

Prior to the conventional experiments, male students strongly held the perception that *chemistry research improves the quality of life* compared to female students (Pre: Male = 6.44, Female = 5.83, $\Delta\text{Mean} = 0.615$, $p = 0.020$). Additionally, prior to, and after exposure to the conventional experiments, male students strongly felt that *science documentaries were more enjoyable* than women did (Pre: Male = 5.79, Female = 5.00, $\Delta\text{Mean} = 0.794$, $p = 0.045$; Mid: Male = 5.51, Female = 4.50, $\Delta\text{Mean} = 1.014$, $p = 0.042$).

ANOVA results prior to the conventional experiments revealed a significant mean difference between Freshmen students and Seniors ($\Delta\text{Mean} = 1.923$, $p = 0.016$), and Sophomore and Seniors ($\Delta\text{Mean} = 1.523$, $p = 0.017$) on their perceptions that *chemistry jobs are satisfying* ($F = 2.897$, $p = 0.044$). Freshmen and Sophomore students had more positive perceptions on this item than Seniors.

The students had positive attitudes (Mean > 3.0) towards undertaking experimental tasks prior to, and after the normal experiments. However, there was no significant improvements on students’ confidence in undertaking experimental tasks following exposure to the conventional experiments (i.e., Mean: Pre = 3.96; Mid = 3.94, $\Delta\text{Mean} = 0.02$, $p = 0.798$, $N = 56$). ANOVA results prior to conventional experiments showed a statistically mean difference between Freshmen and Sophomores ($\Delta\text{Mean} = 2.00$, $p = 0.005$), and Sophomore and Seniors ($\Delta\text{Mean} = 1.115$, $p = 0.024$) on their

confidence in “ensuring that data obtained from an experiment is accurate” ($F = 4.911$, $p = 0.044$) — Freshmen and Senior were more confident than Sophomore. Nevertheless, following the conventional experiments, students felt that *the course did not provide them with opportunities to design experiments*, and that *the experiments were cook-book in structure*. They also showed neutral perceptions about *enjoying the experience in helping with experimental design to answer a question*.

Furthermore, participants perceived the conventional experiments as “standard and simple”, “boring due to “cook-book” procedures”, “lacked creativity”, and “less relevant to their daily-experiences or modern society”. These negative descriptions played a big role in influencing students’ perceptions about chemistry, and the laboratory course in general.

Question 2: How do the undergraduate science major students’ perceptions about, and attitudes toward chemistry and science, and the quantitative analysis chemistry laboratory course, change, if at all, as a result of two inquiry-based integrated nanotechnology-chemistry experiments?

Following exposure to the nanotechnology-chemistry experiments, students had more positive perceptions about chemistry, particularly on the areas discussed above. Statistically significant improvements were noted on students’ perceptions about the flexibility of chemists’ ideas, and chemistry websites. Students felt that *chemists were more flexible in the ideas* (Mid = 4.74, Post = 5.24, $\Delta\text{Mean} = 0.50$; $p = 0.006$), and *chemistry websites were more interesting* (Mid = 4.64, Post = 5.15, $\Delta\text{Mean} = 0.51$; $p = 0.003$) after exposure to the intervention experiments.

Exposure to the intervention experiments also revealed Freshmen had more positive perceptions than Seniors about *chemistry websites being interesting* { $F = 3.723$, $p = 0.017$ ($\Delta\text{Mean} = 2.462$, $p = 0.024$)}, and *chemistry jobs being interesting* { $F = 4.524$, $P = 0.007$ ($\Delta\text{Mean} = 1.734$, $p = 0.039$)}. Similarly, Juniors had more positive perceptions than Seniors on their perceptions about *chemistry jobs being interesting* ($\Delta\text{Mean} = 0.941$, $p = 0.015$), and Freshmen showed more positive perceptions about *chemistry jobs being satisfying* than Seniors { $F = 4.524$, $p = 0.007$ ($\Delta\text{Mean} = 2.000$, $p = 0.024$)}.

Moreover, following exposure to the nanotechnology-chemistry experiments, students showed more positive attitudes ($\text{Mean} > 4$) towards undertaking experimental tasks compared to their attitudes prior to, and after the conventional experiments (Pre = 3.96; Mid = 3.93; Post = 4.03). Significant improvement on students' confidence was noted in "*designing and conducting a chemistry experiment*". Male students displayed more confidence than female students over the semester, with significant mean differences often noted prior to the introduction to the laboratory course. Male students also displayed significantly higher confidence about "*applying chemistry concepts learned to real-world experiences*" than female students did (Post: Male = 4.09, Female = 3.61, $\Delta\text{Mean} = 0.482$, $p = 0.030$) following the intervention. However, females showed more improvement on their confidence over the semester compared to males. Findings also showed that Freshmen and Seniors were more confident than Sophomores in "*ensuring that data obtained from an experiment is accurate*" ($F = 4.911$, $p = 0.044$).

Overall, the results showed that nanotechnology experiments had significant improvement on students' perceptions about the course in question. Following the intervention, students felt that the course afforded them opportunities to help design

experiments (Mid = 2.89, Post = 3.76, Δ Mean = 0.873, $p = 0.000$), and also improved their interest in helping with experimental design to answer a question (Mid = 3.09, Post = 3.53, Δ Mean = 0.436, $p = 0.006$).

Question 3: What factors, if any, influence these students' change of perception about, and attitudes toward chemistry and/or science and the quantitative analysis course?

The major factors for the observed changes in perception and/or attitudinal scores between the mid (following exposure to conventional experiments) and the post mean survey (following exposure to Nanoscale science experiments) include: *the structure of the normal experiments; the structure of the nanotechnology experiments; prolonged laboratory experiences; and contextual factors—student major and competency in the learning.*

The structure of the normal experiments, especially the cook-book procedures often influenced students' negative perceptions about chemistry, and the laboratory course. These perceptions were not only displayed after exposure to the conventional experiments, but were also evident after exposure to the nanotechnology experiments. One explanation for this observation is due to long experience with many conventional experiments compared to few Nanoscale science experiments (i.e., 8 experiments versus 2, respectively). Participants indicated that they learned very little from the recipe- type of the experiments offered in the normal labs, and that the experiments did not offer them opportunities to think critically, or engage in the learning.

The influence due to the nanotechnology experiments were associated with the inquiry-based approach; the relevance of the nanoscale science-based experiments to

real-world and/or students' daily experiences; the novelty of the nano concepts; and the integration of a wide array of chemical instrumentation and equipment in the lessons. The relevance of the nanotechnology-chemistry concepts to real-world positively impacted participants' ability to make connections between the content learned in the classrooms and their daily experiences. Students improved in their perceived abilities to solve environmental issues by applying the concepts they learned in the course.

Some participants developed interest and confidence in the learning, and were able to retain and/or remember the learned concepts more due to real-world experience with the nanoscale science-based experiments. Moreover, many participants indicated that they learned the most from the nanoscale science-based experiments due to the real-world connection to the classroom experience. The novelty of the nanotechnology concepts improved students' curiosity and interest in the learning, as well as their perceptions about chemists. Furthermore, integration of a wide array of chemical instrumentations and equipment in one lesson session fostered students' understanding of the complex analytical techniques such as GC and scanning UV-visible spectrometry. This integration also helped students to see the relevance and application of multiple techniques in solving a real-world problem.

Prolonged lab experiences influenced students' change of perceptions both negatively and positively. Some students indicated that they improved on their perceptions after long exposure to the techniques and the types of experiments. Contextual factors such as student major and self-competency in the learning may influenced the participants' change of perception, even though this factor was demonstrated by one participant.

Question 4: What are the perceptions and attitudes of undergraduate science majors towards inquiry-based learning?

Results indicated that students had less positive perceptions about inquiry-based learning following the convention experiments. However, following the intervention experiments, students' perceptions about the laboratory activities, the instructional approach, and their own learning improved, with some significant improvement noted on students' perceptions on the following areas:

- 1) The relevance of the activities to real-world experiences;
- 2) Opportunities to establish research questions;
- 3) Instructor's support in the learning;
- 4) Effectiveness of group learning in developing shared goal;
- 5) Group support in the learning;
- 6) Ability to find information from different sources; and
- 7) Ability to apply the concepts learned in the course to solve environmental issues in society.

Overall, following the intervention, students valued the inquiry-based approach, especially in devising experimental procedures; asking and finding answers to their questions; and searching for relevant information for data interpretation and in writing lab reports, with minimal guidance from the instructor. Most importantly, a large number of the participants felt that they learned the most from the Nanoscale science experiments because they had control over their own learning; they developed critical thinking skills; could formulate researchable questions; and could relate the content and classroom experiences with the real-world.

In summary, results showed that nanotechnology is a conduit for increasing student perceptions about, and attitudes towards chemistry and science, as well as promoting interest for progression into science-related careers. Many students felt that they learned the most from the nanotechnology labs than the normal labs. The nanoscale science-based experiments also elicited positive interest towards nano-related research jobs. I contend that integrated nanotechnology-chemistry curriculum helped students connect to, and engage in chemistry in novel and exciting ways. Furthermore, inquiry-based learning approach is well received by science major students, particularly those in advanced class levels (e.g., junior and senior students).

Implications for Practice

The findings of this study imply key reforms in the undergraduate chemistry laboratory curriculum. First, classroom instructional practices in higher institution should be reformed to embrace student-centered or research-based instructional approaches in which students can have autonomy in the learning. These evidence-based approaches to teaching and learning such as inquiry should be integrated in advanced science courses, including chemistry, and not just in the general chemistry labs as evident in the literature. While many researchers have focused on the general chemistry courses as gateways to attract students into this field, there is a need to think about effective ways of retaining those students already in the STEM fields. Shortage of future STEM workforce will continue to be experienced, especially in the U.S. if institutions of higher learning continue to lose STEM majors to non-STEM fields.

Results clearly indicate that the recipe-type of experiments are not effective in promoting students' positive attitudes or perceptions towards learning; rather they are perceived as "boring" tasks that students have no interest in. Participants in this study valued inquiry-based approach over the expository teaching method. It was alarming to uncover that most of the participants being juniors and seniors; they had no prior experience with the inquiry approach. This is in line with the findings reported by Abraham et al. (1997), Hilosky et al. (1998), and Domin (1999) that teaching in many chemistry departments conforms to the expository method, even when laboratories should provide student with a feel of scientist-like practices.

Teaching in many universities has been dominated by the overemphasis on content knowledge (Gilbert, 2006; Holbrook, 2005) and little focus on relevant skills important in preparing students for future workforce (Carnevale, 2010). Findings in the current study revealed that students felt their role in learning is to fulfill what the instructors and the departments, or the university require them to do in order to be conferred with their degrees. Many felt that their role in the laboratory learning is to show up, collect data, and leave the lab. The only effort they have to put in is compiling laboratory reports, which count towards their final grade, and eventually to their degree. For instance, participant M54 said:

It's just like right now I'm just like a rat with chemistry, so you say we have to take this to get my degree, so I will do it.... Ever since I got to college, I have been told what to take, not to take, and what I can't take, so that's my learning in a whole. In the lab it was the same thing; you tell me what to do, I do it, get my degree and move on... It's just being in the college and not having control over what I'm learning.

With the anticipated increase in STEM workforce by 2018 and beyond, it is important that universities restructure STEM curricula and teaching approaches to address the needs of students and society at large.

Second, institutions should incorporate context-based curriculum to increase students' attitudes and perceptions towards advanced science courses as well as progression into the science careers of the 21st Century. The results indicate that theoretical concepts alone are fruitless in equipping students with scientific knowledge and skills relevant in solving problems in real-world. There is a need to provide students at all levels with real-world objects or items related to applications of the concepts being taught to reinforce relevance, which, in turn can promote student interest in the learning, as well as understanding and retention of the concepts.

In this study, students valued relevance of the concepts to their needs and society. Some participants indicated that they developed interest towards the nanoscale science lessons, and were able to retain the learned concepts in these lessons due to the relevance of the concepts to real-world and/or everyday life experiences. Therefore, integrating “contexts” that reflect real-life situations into the existing-chemistry curriculum may be a powerful tool for increasing student interest and motivation towards chemistry. Nanotechnology is one such context that can enhance the relevance of chemistry and/or science concepts to students. It is important that real-life contexts be embedded not only in the introduction section of each laboratory experiment, but also in the textbooks intended for in-class readings or assignments. This may serve as a “hook” to increasing students' interest in the course, as well as improving their conceptual understanding. For instance, in the current study, one student asserted that *“I liked the intro [embedded in*

the Nanoscale science experiments] because it helped understand the concepts better”

(Source: classroom observation video and notes).

Third, departments should consider developing a curriculum that familiarizes students with advances in modern society through chemistry research, as well as help them to see the applicability of the content and/or techniques they learn in classrooms to real-world. One way to achieve this is by incorporating field trips as part of the undergraduate curriculum, in which students will be provided with opportunities to visit chemistry-related industries or plants to become familiar with different types of chemistry research jobs. This could also be achieved by incorporating novel concepts that have received attention in the media in the curriculum. It is undoubtedly that novelty sparks one's curiosity and interest in the learning. In this study, students indicated that the novelty of the nanotechnology increased their interest in learning the nanotechnology experiments. This, in turn, enhanced their understanding of the Nanoscale science concepts.

Another way is to develop a 1-or 2-credit-hour seminar course, where students could interact with invited speakers from chemistry-related industries, or chemists working on different cutting-edge research, to share their journey experiences to becoming expert chemists. The implementation of such curriculum should take place during the early stages of the students' undergraduate education. This move is also likely to promote positive attitudes and perceptions towards chemistry as well as create awareness on the variation of chemistry jobs, the relevance of chemistry research in solving issues in society, and the key role played by chemists in modern society. Ultimately, this is important in ensuring progression into advanced chemistry courses

and/or chemistry-related jobs, especially underrepresented minorities, including women. Nevertheless, a collaborative effort between chemistry departments and chemical industries is vital in producing competent citizens who can be a part of the projected workforce in the 21st century.

In summary, it is important for schools and institutions of higher learning to recognize the pivotal role played by student attitudes and implement curricula and teaching approaches that promote positive perceptions and attitudes toward learning.

Future Research Work

The current study is a design-based research in which the researcher attempted to evaluate the impact of two integrated Nanoscale science modules on students' perceptions and attitudes towards chemistry, and a laboratory course. Although the findings showed some improvements on students' perceptions and attitudes following the Nanoscale science experiments, the calculated effect size was small due to the limited number of nanotechnology experiments in comparison to the conventional experiments. Future researchers should attempt to integrate equivalent number of Nanoscale science experiments as the conventional experiments, as well as evaluate the impact of the intervention on students' affective domain.

Furthermore, the study was conducted using one sample. Future researchers could consider carrying out an experimental study in which the perceptions of the treatment group are compared to a control group not exposed to the Nanoscale science experiments. Additionally, future research could attempt to evaluate the impact of integrated nanotechnology-science curriculum on students' conceptual understanding of the science

concepts. Although research on the impact of nanotechnology education on students' conceptual understanding has been reported (e.g., Daly et al., 2007; Furlan, 2009; Lee et al., 2006; Moyses, 2010), the incorporation of the nanotechnology concepts have been introduced as a single discipline. Therefore, very little is known about the impact of integrated nanotechnology-science curriculum, including chemistry, on the achievement scores of STEM majors in undergraduate level. Uncovering this information will provide insights for preparation of future nanotechnologists needed in the anticipated trillion dollar nanotechnology industry (Meyyappan, 2009; NNI, 2012), as well as the anticipated future STEM workforce.

Finally, the findings indicated that students valued contexts that reflect real-world experiences, as this elicited their interest in the learning, as well as conceptual understanding of the nanotechnology concepts. They felt that the normal laboratory experiments lacked relevance to their daily-lives. Consequently, they indicated that they learned very little from the course in question. Context-based learning, especially pertaining environmental applications should be incorporated to future quantitative analysis/analytical chemistry courses to elicit students' interest in the course, while equipping them with the relevant know-how. Future research work should also strive to evaluate the extent of integration of real-world contexts in the chemistry laboratory manuals and common chemistry textbooks. Information gathered from such evaluations could be useful in informing future improvement of the chemistry curriculum. The content analysis should also investigate the alignment of the chemistry content with the American Chemical Society (ACS) chemistry goals, as well as required graduate skills in

current and future chemistry or science-related job market. The following research questions should guide future research work:

1. How do the perceptions and attitudes towards chemistry, and chemistry courses differ between students exposed to the integrated nanotechnology-chemistry curriculum and those not exposed to the same curriculum?
2. What is the impact of integrated nanotechnology-chemistry curriculum on students' conceptual understanding of the science concepts?
3. What type of contexts are depicted in the commonly used college level chemistry texts, and chemistry laboratory manuals or modules in the U.S.?
4. How do these contexts, if any, align with the ACS chemistry goals?
5. How does context-based curriculum influence undergraduate preparedness for the job market?

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APPENDIX A

Survey Instruments

Chemistry Attitudes and Perceptions Survey #1—adopted from *Dalgety, Coll, and Jones (2003)*

The information you submit in this survey will NOT be reported on individual basis. It will be reported on an aggregate level.

Section 1: Demographic Information

Student Identification #: ----- Gender -----

Your current GPA ----- How many hours do you study per week? -----

Years of chemistry including high school and university -----

Section 2: Survey Items

PERCEPTIONS

- 1) Please rate the perceptions you have about chemistry and related topics. For example, if you feel chemistry is mostly about the study of natural substances, and only a little bit about the study of synthetic material then mark your answer like this:

Chemistry: Natural substances ☐ ☒ ☐ ☐ ☐ ☐ ☐ Synthetic Material

Chemists

Socially aware	<input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/>	Socially unaware
Environmentally unaware	<input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/>	Environmentally aware
Fixed in their ideas	<input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/>	Flexible in their ideas
Care about the effects of their results	<input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/>	Only care about their results
Imaginative	<input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/>	Unimaginative
Unfriendly	<input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/>	Friendly
Indifferent	<input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/>	Inquisitive
Patience	<input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/>	Impatient

Chemistry Research

- | | | |
|-------------------------------|---|------------------------------|
| Helps people | <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> | Harms people |
| Decreases the quality of life | <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> | Improves the quality of life |
| Solves problems | <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> | Creates problems |
| Advances society | <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> | Causes society to decline |

Science Documentaries

- | | | |
|---------------|---|-------------|
| Enjoyable | <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> | Boring |
| Uninformative | <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> | Informative |

Chemistry web sites

- | | | |
|-------------|---|--------|
| Interesting | <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> | Boring |
|-------------|---|--------|

Chemistry Jobs

- | | | |
|-------------|---|--------------|
| Challenging | <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> | Easy |
| Varied | <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> | Repetitive |
| Interesting | <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> | Boring |
| Satisfying | <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> | Unsatisfying |
| Exciting | <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> | Tedious |

CONFIDENCE

2) Please rate the confidence you have in undertaking different tasks:

1 = Totally confident; 2 = Somewhat Confident; 3 = Undecided; 4 = Somewhat Unconfident; 5 = Not at All Confident

- | | 1 | 2 | 3 | 4 | 5 |
|--|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| b. Reading the procedures for an experiment and conducting the experiment without supervision----- | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> |
| c. Designing and conducting a chemistry experiment----- | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> |
| d. Tutoring another student in a second year chemistry course----- | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> |
| e. Determining what answer is required from a written description of a chemistry problem----- | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> |
| f. Ensuring that data obtained from an experiment is accurate----- | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> |
| g. Proposing a meaningful question that could be answered experimentally---- | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> |
| h. Explaining something that you learnt in this chemistry course to another person ----- | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> |
| j. Know how to convert data obtained in a chemistry experiment into a result--- | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> |
| k. After reading an article about a chemistry experiment, writing a summary of the main points----- | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> |
| l. Learning chemistry theory----- | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> |
| n. Writing up the experimental procedures in a laboratory setting----- | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> |

- o.** After watching a television documentary dealing with some aspects of chemistry, writing a summary of its main points----- ○ ○ ○ ○ ○
- q.** Applying theory learnt in a lecture for a laboratory experiment----- ○ ○ ○ ○ ○
- r.** Writing up the results section in a laboratory report----- ○ ○ ○ ○ ○
- s.** After listening to a public lecture regarding some chemistry topic, explaining its main ideas to another person----- ○ ○ ○ ○ ○
- t** Applying chemistry concepts learnt to real-world experiences----- ○ ○ ○ ○ ○

Inquiry-Based Learning Environment Survey #2—adopted from *Moore (2006)*

The information you submit in this survey will NOT be reported on individual basis.

Section 1: Demographic Information

Student Identification #: -----

Section 2: Survey Items

For each statement, tick one box to indicate your response as follows:

1 = strongly disagree

2 = disagree

3 = neither agree or disagree

4 = agree

5 = strongly agree

	Statement		1	2	3	4	5
1	I feel that I understood the learning process this far						
2	I learned about how to present my findings to an audience						
3	I found the activities easy						
4	These activities helped me to develop my team working skills						
5	I learned how to plan my learning						
6	During the modules, I was given opportunities to establish my own research questions						
7	The instructor focused more on encouraging me to find information than on giving me the facts						
8	The activities were more about analyzing and evaluating information than they were about memorizing them						
9	I feel I am better able to find information from different sources						
10	I am more confident in my ability to evaluate the information I have found						
11	I feel I am better able to evaluate different sources of information						
12	I needed a lot of support from the instructor in these activities						
13	These activities helped me to discover what was expected of me as a learner						
14	The group was effective in developing shared goals						
15	I enjoyed working in this way						
16	I needed support in establishing my own questions to research						
17	I found the team members to be helpful in my learning						
18	I didn't need to apply anything I learned						

Confidence Survey Instrument—Continued

	Statement		1	2	3	4	5
19	I had opportunities to lead the group						
21	There was a lot to learn						
22	I enjoyed working as a member of a team						
23	I feel I am better able to communicate with others						
24	Any interpersonal difficulties were cleared up in a positive manner						
25	I felt I had to work hard to complete the activities						
26	My group worked well as a team						
27	I felt I was able to take more responsibility for my own learning						
28	As a result of the activities, I am now more confident about my ability to establish my own research questions						
29	The group worked well to overcome any difficulties or problems we encountered						
30	I found the activities challenging						
31	I can see a range of ways in which I can contribute to a group task						
32	I feel more confident in my ability to solve problems						
33	The group appreciated my inputs						
34	I felt I could get through the activities simply by memorizing things						
35	I felt a sense of control over my learning						
36	I feel I am better able to present my findings						
37	The instructor gave me the support I needed to learn in these experiments						
38	I developed an understanding of technical processes through working with my group						
39	I was able to see good ways of presenting information						
40	I can see how the activities relate to things that I'm interested in						
41	I found the activities relevant to real-world experiences						
42	I can apply the concepts I have learned in this lab course in solving environmental issues in society						

Attitudes and Perceptions Survey #3—adopted from *Lewis and Seymour (2004)*

The information you submit in this survey will NOT be reported on individual basis.

Section 1: Demographic Information

Student Identification #: -----

Section 2: Survey Items

In this section, use the 5-point scale to indicate your agreement or disagreement with each statement. Please circle one choice only.

ORGANIZATION

strongly disagree
disagree
neutral
agree
strongly agree

LAB

- | | | | | | | |
|-----------|--|----------|----------|----------|----------|----------|
| 8 | Often in lab I didn't understand the concept behind the lab experiments. | 1 | 2 | 3 | 4 | 5 |
| 9 | I like labs where I get to help design an experiment to answer a question. | 1 | 2 | 3 | 4 | 5 |
| 10 | This course provided opportunities for me to help design experiments to answer a question. | 1 | 2 | 3 | 4 | 5 |
| 11 | It was clear how the lab experiments fit into this course. | 1 | 2 | 3 | 4 | 5 |
| 12 | Doing labs in this class was like following a recipe in a cook-book. | 1 | 2 | 3 | 4 | 5 |
| 13 | The lab manual for this course was well-written (easy to understand). | 1 | 2 | 3 | 4 | 5 |

Learning Environment

Assuming that all the following activities are equally well-implemented, **I learn well by ...**

strongly disagree
disagree
neutral
agree
strongly agree

- | | | | | | | |
|-----------|------------------------------|----------|----------|----------|----------|----------|
| 37 | working with my lab partner. | 1 | 2 | 3 | 4 | 5 |
|-----------|------------------------------|----------|----------|----------|----------|----------|

39	doing hands-on activities.	1	2	3	4	5
40	listening to lecture.	1	2	3	4	5
45	completing lab notebooks or lab reports.	1	2	3	4	5
46	reading and re-reading materials.	1	2	3	4	5
	I know I understand when ...	1	2	3	4	5
49	I can work problems in the book.	1	2	3	4	5
50	I can apply ideas to new situations.	1	2	3	4	5
51	I get a good grade on an exam.	1	2	3	4	5
52	I can explain the ideas to someone else.	1	2	3	4	5
53	I can see how concepts relate to one another.	1	2	3	4	5

Section 3: Open-ended questions

In this section, provide your responses to the questions below.

Based on all the experiments you carried out in this course (CHEM 2260) this semester:

- a) Which experiment do you feel you learned the most from?

Describe the reasons for your choice in (a) above.

- b) Which experiment do you feel you learned the least from?

Describe the reasons for your choice in (b) above.

- c) Which experiment do you feel helped you to see the relevance of chemistry to modern society and/or to daily-experiences?

Briefly describe how it promoted the relevance or addressed your needs.

APPENDIX B

Interview Protocol

Hello, thank you for coming. This interview consists of two parts. In part 1 of the interview I will ask you to describe your perceptions about the analytical chemistry laboratory course you took this semester. In part 2, I will ask you to reflect on your survey responses based on the three questionnaires that you filled out at the mid and the end of the semester, and explain why your perceptions changed with regards to specific survey items, which I will be able to identify for you.

PART 1: General Laboratory Perceptions/Experiences

1. Describe your perceptions about the analytical chemistry lab course (CHEM 2260) you took this semester.
2. What is your general view about the normal laboratory experiments (the non-nanotechnology) that you were exposed to in this course?

Prompt: What did you like about them?

Prompt: What did you not like about them?

3. Describe your perceptions about the nanotechnology units that you were introduced to.

Prompt: What did you like about them?

Prompt: What did you not like about them?

4. Was any of the methods of instruction useful in helping you learn the concepts better? If, so, which one?

Prompt (If necessary): Describe your experiences in learning through the inquiry-approach (where you were given an opportunity to design your experiment—TA let you be responsible for your own learning).

5. What other thoughts/comments do you have regarding:
 - The inquiry-based learning approach?
 - The nanotechnology laboratory experiments in terms of the content?
6. If you were the instructor for this course in the subsequent semester, what changes do you think you would make on the experiments?

PART 2: Changes in Survey Responses

1. Based on your responses to the mid-survey, you indicated that (insert appropriate responses...) while in the post survey you changed your scoring of item (insert item...) from (score... to). Please explain why you changed your perception on this item.

APPENDIX C

Human Subject Institutional Review Board Approval Letter

WESTERN MICHIGAN UNIVERSITY



Human Subjects Institutional Review Board

Date: September 8, 2011

To: Sherine Obare, Principal Investigator
Megan Grunert, Co-Principal Investigator
Jacinta Mutambuki, Student Investigator for dissertation

From: Victoria Janson, Interim Chair

A handwritten signature in cursive script, reading "Victoria Janson".

Re: HSIRB Project Number 11-07-19

This letter will serve as confirmation that your research project titled "Integrating Nanoscience and Nanotechnology into the General Chemistry Curriculum: Authentic Learning" has been **approved** under the **expedited** category of review by the Human Subjects Institutional Review Board. The conditions and duration of this approval are specified in the Policies of Western Michigan University. You may now begin to implement the research as described in the application.

Please note that you may **only** conduct this research exactly in the form it was approved. You must seek specific board approval for any changes in this project. You must also seek reapproval if the project extends beyond the termination date noted below. In addition, if there are any unanticipated adverse reactions or unanticipated events associated with the conduct of this research, you should immediately suspend the project and contact the Chair of the HSIRB for consultation.

The Board wishes you success in the pursuit of your research goals.

Approval Termination: September 8, 2012

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