Negotiating the Inclusion of Nanoscience Content and Technology in Science Curriculum: An Examination of Secondary Teachers' Thinking in a Professional Development Project

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Negotiating the Inclusion of Nanoscience Content and Technology in Science Curricula: An Examination of Secondary Teachers' Thinking in a Professional Development Project

by

Jennifer Gayle Wells

A dissertation submitted in partial fulfillment of the requirements for the degree of

Doctor of Education
in
Educational Leadership: Curriculum and Instruction

Dissertation Committee:
Karen Noordhoff, Chair
Samuel Henry
Carl Wamser
Sybil Kelley

Portland State University
2013
Abstract

The Next Generation Science Standards represent a significant challenge for K-12 school reform in the United States in the science, technology, engineering and mathematics (STEM) disciplines (NSTA, 2012). One important difference between the National Science Education Standards (NRC, 1996) and the Next Generation Science Standards (Achieve, 2013) is the more extensive inclusion of nanoscale science and technology. Teacher PD is a key vehicle for implementing this STEM education reform effort (NRC, 2012; Smith, 2001).

The context of this dissertation study is Project Nanoscience and Nanotechnology Outreach (NANO), a secondary level professional development program for teachers that provides a summer workshop, academic year coaching and the opportunity for teacher participants to borrow a table-top Phenom scanning electron microscope and a research grade optical microscope for use in their classrooms. This designed-based descriptive case study examined the thinking of secondary teachers in the 2012 Project NANO cohort as they negotiated the inclusion of novel science concepts and technology into secondary science curriculum.

Teachers in the Project NANO 2012 summer workshop developed a two-week, inquiry-based unit of instruction drawing upon one or more of nine big ideas in nanoscale science and technology as defined by Stevens, Sutherland, and Krajcik (2011). This research examined teacher participants’ metastrategic thinking (Zohar, 2006) which they used to inform their pedagogical content knowledge (Shulman, 1987) by focusing on the
content knowledge teachers chose to frame their lessons, their rationales for such choices as well as the teaching strategies that they chose to employ in their Project NANO unit of instruction. The study documents teachers various entry points on a learning progression as teachers negotiated the inclusion of nanoscale science and technology into the curriculum for the first time. Implications and recommendations for teacher professional development are offered.
Dedication

This work is dedicated to emerging scientific thinkers who are enabled to pursue knowledge, skills and wisdom thanks to their own natural curiosity and wonder and to educators and mentors who believe in their ability to learn.
Acknowledgments

The teachers and teacher leaders who participated in Project NANO have been absolutely amazing in the level of support and openness with which they have approached this work. In a very true sense, the Project NANO team and the teacher participants worked as co-investigators to contribute to the small but growing body of knowledge about how teachers navigate the inclusion of nanoscale science and technology into the curriculum. It is worth noting repeatedly throughout this document that 100% of the teachers submitted all of the requested data to the researcher and in many cases, teachers offered more data than was requested. Teachers ate lunch with me, met after school, spent planning periods with me and otherwise went far beyond the call of duty to share their thinking with me. They shared information between and among members of the Project NANO cohort of teachers and their coaches in creative and practical ways that lifted the experience for all involved into new possibilities of thinking and learning. I am forever grateful for their incredible contribution to Project NANO and to this study.

Dr. Sherry Cady has been a driving force behind Project NANO and this dissertation study. Her sense of passion, vision and belief in the ability of people to cross boundaries and think in new ways about complex, ill-defined problems is an inspiration to me and to the entire Project NANO team. I am grateful for what I have learned from working with Dr. Cady and the opportunities that she worked very hard to provide in the service of teachers, myself and ultimately the children who have the opportunity to expand their sense of the natural and built world through the Project NANO experience.
I am grateful for the support of the M. J. Murdock Charitable Trust for providing resources to Project NANO to engage the creative scientific minds of our teachers and youth who without fail conveyed deep gratitude for this expression of belief in the potential of the next generation. At a time when students are given the blatant message that fostering their development is a marginalized priority in our society, I wish to express my profound sense of excitement and hope that the Murdock Trust believes that teachers and children are worth the investment. Thank you for investing in the teachers and children and thank you for investing in my graduate research assistantship that made this work possible.

The people at the Center for Science Education have also been instrumental in contributing to the formation of my thinking and of my life as a teacher professional developer and researcher. The partnerships between disciplinary faculty, science education faculty and school district teachers on special assignment has led to incredibly innovative thinking that I believe is “turning the dial” in fundamental ways to support teachers to improve science education cradle through career. Dr. Cary Sneider, Dr. Sybil Kelley, Dr. Carl Wamser, Dr. Linda Mantel, Dr. Bill Becker, Dr. Melissa Potter, Dr. Ellen Lyon, Stephanie Wagner, Mike Blok, Keith Grosse, Nancy Lapotin, Carol Biskupic-Knight, Chris Steiner, Will Walker, Stephen Scannell, Jesse Southwick, Aaron Osowiecki, Elizabeth Lipes, Steve Day, Nicole Rigelman, Emily Saxton, and all of the masters level students and my beloved graduate assistants have been instrumental in my development. I am grateful to the Center for providing me with an intellectual home, with a strong base of support and with many opportunities to laugh along the way.
The Language, Literacy, Technology and Research group in the Department of Applied Linguistics has also served as my rock throughout the dissertation experience. Their words of wisdom at key points along the way inspired innovative ideas for how to sort, code and interpret data. They have expanded my sense of how people communicate, think and learn and embraced me and my work in a multitude of small and huge ways that made this work possible, not to mention providing me with an office space with real walls, a window and door that closes instead of an open cubicle, a resource that has been essential to the timely completion of this study and doctoral degree within a healthy academic community.

My dissertation cohort supported my work with undying patience and tenacity that I will never forget. This group of six students and two faculty advisors participated in a journey of intellectual intimacy that helped me to stay grounded with the true motivations for pursuing the doctorate and completing this dissertation, improving the education of teachers and ultimately, children. I could not have done this work without the wise intelligence of this group who held up mirrors to show me things in my blind spots and radiated into the darkness when I needed to remember the light. Each member of this cohort conducted research that I would have loved to pursue; thus, I am grateful to have had the opportunity to learn from their experiences and gain new ways of looking at teaching, learning and research as a result of their hard work.

I read in the Chronicle of Higher Education that once you enter a doctoral program, your advisors become much like parents. This has, in many ways, been the case for me over the past 4 years. My dissertation committee chair, Dr. Karen Noordhoff, has
been instrumental in my intellectual and in many ways, emotional growth, as I shed my former identity and assumed the mantle of researcher and doctoral level thinker. Her steadfast commitment to constructivism, although admittedly frustrating at times, taught me a great deal about how to advise students as well as provided me with the room to deeply examine my own metastrategic thinking and pedagogical content knowledge (PCK) as my content knowledge and research and writing abilities expanded tremendously. I know that I am a much better writer than I was before entering the program, thanks in large part to the intensely rigorous process of working with an advisor who strives for extremely high quality work. I am grateful to have caught the tail of her kite just before she finally retires from university life and enters more fully into her work with the Courage and Renewal community and her family life. I consider myself blessed to have been provided with such a wise and knowledgeable mentor.

My dissertation committee is comprised of some of the dearest colleges in my academic life. Dr. Samuel Henry served as the second faculty advisor for our cohort as well as worked with me as a co-investigator for the Robert Noyce Teacher Scholars program. He has been an incredible guide for my work as well as provided our entire cohort with many practical ideas for how to navigate within the political world of education. His work on the state level to improve education both informs my work and aspirations as well as makes me proud to consider him a true friend and colleague.

Dr. Carl Wamser, who served as the Graduate Office Representative on my committee also worked with me on the Robert Noyce Teacher Scholars Program as a co-investigator. As is the case with Dr. Henry, Dr. Wamser was instrumental in guiding and
supporting my transition from working at the K-12 level to serving as a university level teacher professional developer and researcher. His deeply insightful perspective as a veteran university-level chemistry educator and steadfast supporter of science education is an inspiration to me. Given that Dr. Wamser officially retired last spring of 2012, I am particularly grateful that just one last time, he said “yes” to yet another request that he collaborate with me to make a contribution to science education.

Similarly, Dr. Sybil Kelley, the fourth member of my dissertation committee, deeply inspires my thinking in great and profound ways. As a colleague who was also intellectually nurtured over the past decade at the Center for Science Education, she understands both the scientific aspects of my work and the educational theory of practice that guides this dissertation. I know that I am truly blessed to have the support of this long-time colleague who is on the same page with me in terms of the foundational constructs that guide my own practice. After many years of working in parallel, I am grateful that this dissertation finally provided us with the opportunity to collaborate, and on one of my most important projects to date no less! Her suggestions related to the constructs of learning progressions and adaptive expertise propelled me to better discern how this research is situated in the field of science education and raised this work to new heights. I am grateful for both her intellectual support and her dear friendship.

Dean Randy Hitz of the Graduate School of Education has served as an important mentor and colleague throughout this experience. His career planning guidance, instruction on how to publish and otherwise disseminate my work has placed me in an excellent position to take the next steps in my career. Our work together to support the
Faculty Senate Teacher Education Committee and statewide Oregon Coalition for Quality Teaching and Learning has been both inspiring and filled some critical gaps in my knowledge related to current educational policy, politics and mechanisms of reform. I am grateful to him for his patience and willingness to answer even the most mundane of my questions with an open-mind.

I must further acknowledge the giants upon whose shoulders I stand on. The team of science education leaders who developed the NSTA Big Ideas in Nanoscale Science (2009) did a great deal to enhance my understanding of the nanoscale concept and to develop a sense of what teachers’ learning progressions might look like in this context. The National Center for Learning and Teaching in Nanoscale Science and Engineering publications provided me with a huge leg-up throughout the design process of Project NANO and of this dissertation study. Their seminal work also deeply influenced the internal evaluation design for Project NANO, which will serve the program well long after I’ve departed from the team. Lee Shulman’s (1986;1987) and Magnusson, Krajcik, and Borko’s (1999) seminal work on the pedagogical content knowledge framework and Veal’s (1999) work on taxonomies of pedagogical content knowledge serve as foundational building blocks upon which this dissertation is built. Ben-David and Zohar’s (2009) work on metastrategic knowledge both challenged and inspired me to think expansively about how teachers’ think and learn. Loughran, Berry, and Mulhall’s (2006) work to develop Resource Folios served to unlock teachers’ thinking in a way that was previously inaccessible to me as a researcher and teacher professional developer. I am grateful for the books and papers they published that guided my work as well as the time
Dr. Loughran spent with me at the AERA conference this year helping me to think about how to structure my findings and consider next steps with disseminating this work.

And finally, I want to acknowledge the support of my family. My own parents’ belief and my husband’s parents’ belief in my potential and capabilities never fail to amaze me. I am inspired by their parenting skills and their ability to go with the flow and support us wherever our aspirations led us. My Mother’s careful eye caught many spelling and grammatical errors and pointed out sections that did not make sense. Her careful editing support will surely make reading this manuscript a more enjoyable experience for all who read this work. My husband Rob’s untiring belief in my ability to successfully accomplish this work and contribute to the field in the short amount of time available in this lifetime was absolutely crucial to this entire enterprise. He pitched in to help in ways that go way beyond the marriage vows that we share between us. He is a true intellectual and emotional soul mate. I am undyingly grateful that he puts up with me and keeps me laughing and smiling.

My young son Gavin, who has never known a mommy that was not a doctoral student, has been a constant source of inspiration and support. I am grateful for his patient and kind temperament and his profound ability to be my companion throughout countless hours of study, reflection, and writing. Hanging on my office door I have a quotation from Martin Luther King Jr. that I will one day say to my own son who inspires so much of what I do: “I said to my children, ‘I am going to work and do everything that I can do to see that you get a good education. I don’t want you to forget that there are millions of God’s children who will not and cannot get a good education, and I don’t
want you feeling that you are better than they are. For you will never be what you ought to be until they are what they ought to be.””

To all of you I say, thank you. Thank you for the love and support you have given to me and thank you on the behalf of children who will one day benefit from this and similar work so that one day, they may be what they ought to be.
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CHAPTER ONE
INTRODUCTION AND OVERVIEW

The word literate most commonly refers to the ability to read and write. But the term literate can also mean learned or competent to function minimally in society (Laugksch, 2000). Beginning in the late 1950s, people in the U.S. began to include scientific literacy as part of what would become considered basic knowledge necessary for the rising generations of Americans to function well in society (Laugksch, 2000). The enduring perception is that a basic level of scientific literacy involves the ability to comprehend and resolve ambiguity of ideas and the ability to communicate ideas that convey meaning about observed natural phenomenon (Fenichel & Schweingruber, 2010).

Messages from research studies, government reports and policies and the daily newspapers emphasize the demand for an increasingly high level of scientific literacy necessary to navigate the complexity of a world filled with rapidly advancing science and technology. To ensure that the rising generation is prepared as scientifically literate citizens, K-12 teachers must be provided with pragmatic, effective professional development (PD) so that the latest technologies, content knowledge and effective pedagogical strategies are strategically incorporated in classrooms (Bryk & Gomez, 2007; National Commission on Mathematics and Science Teaching, 2000).

Identifying what concepts to teach is the job of the syllabus or curriculum, but the nature and structure of each concept, and how connected concepts relate to the real world, are generally poorly defined and are left up to the teacher to decipher. Berliner (1988)
made clear that teaching for understanding is based on a teacher’s professional scholarship of practice. Knowledge of disciplinary content, how to present and scaffold information, and understanding of the unique developmental needs of particular groups of students and the individuals within each class characterizes the complex, interwoven practice of teaching (Loughran, Mulhall, & Berry, 2008). Given the nature of science, the rapid advancement of technology and humankind’s constantly evolving understanding of how to study and interpret the natural world, career-long science teacher PD is necessary to ensure that educators have ability to weave new concepts and technology into their corpus of knowledge.

Rowan, Correnti, and Miller (2002) documented significant positive effects of content-based teacher PD in supporting teachers’ ability to interpret the pedagogical implications of content so that they may more effectively choose and implement teaching strategies that improve student learning outcomes for all students, including learners with special needs. By working in community with others, teachers deepen their own content knowledge and teaching skills by reflecting with colleagues to identify effective and less effective instructional strategies to expand their depth of content knowledge and instructional repertoires (Smith, 2001).

Shulman (1987) referred to this amalgam of content knowledge and pedagogical knowledge as Pedagogical Content Knowledge (PCK). Shulman (1986) described PCK as a teacher’s knowledge of the dimensions of subject matter for teaching using the most effective means of, “representing and formulating the subject in a way that is comprehensible to others [and] understanding what about the subject matter makes it easy
or difficult for students to understand” (p. 9). He acknowledged that there is not one-best way or best activity to teach topics, but that teachers develop a “veritable armamentarium” (Shulman, 1998, p. 9) of representations some of which are derived from their own experiences as a teacher and others from research.

Since Shulman’s (1986, 1987) initial presentation of the idea of PCK in the late 1980s, this construct has become widely accepted in academia. The awareness of the importance of supporting the development of teachers’ content knowledge in the context of exploring implications for teaching and learning represents a significant shift in the way teacher PD is designed in the U.S.

Affecting teachers’ PCK is not an easy thing to achieve, especially in a way that induces significant changes in classroom practice (Zohar, 2006). I submit there are four main issues–some of which are related to teachers’ content and PCK–that prevent success in secondary level science, technology, engineering and mathematics (STEM) reform initiatives in the United States. In the Chapter Two literature review, these four issues are grounded in the empirical literature. These four limitations include:


- Limited curricula that fail to keep up with leading edge STEM knowledge (Hurd, 2002; Schank, Krajcik, & Yunker, 2007).

- Teacher’s limited knowledge of instructional strategies (pedagogical knowledge) for effectively integrating technology into the classroom (Healy, 2009; Schank et al., 2007; Shulman & Sparks, 1992).

- A lack of effective teacher professional development models that explicitly incorporate and highlight specific teaching practices, as well as provide a
basis of rationale for choosing one strategy over another to incorporate leading edge technology into a secondary classroom (PCK) (Bryan et al., 2007; Madden et al., 2007).

**Project Nanoscience and Nanotechnology Outreach**

Project Nanoscience and Nanotechnology Outreach (NANO), is an approach to teacher PD that addresses the limitations I just described. The program draws upon the teacher PD standards established by the National Staff Development Council (NSDC, 2012) Learning Forward Program and current research on effective practices in science teacher PD to offer a program that provides teachers with new and existing content presented with the context of authentic science inquiry and supports the development and implementation of units of instruction that include topics related to the nanoscale.

Nanoscale science and technology involves imaging, measuring and manipulating matter at the length scale of one billionth of a meter (Nano.gov, 2012). To give a sense of how small a nano is, a sheet of paper is about 100,000 nanometers thick and there are about 25,400,000 nanometers in one inch (Stevens, Sutherland, & Krajcik, 2011).

Project NANO has been developed over the past three years by two veteran high school chemistry and biology teachers, a veteran Professor of Geology and me, a faculty member with a university-based Center for Science Education and Graduate School of Education. The collective efforts of Project NANO have created a design-based PD program that involves training teachers to use a scanning electron microscope, a research grade compound microscope and a dissecting microscope as inquiry tools for enhancing secondary level teaching and learning. This study examines teachers’ metastrategic thinking (Zohar, 2006) and PCK (Shulman, 1987) as they negotiated the inclusion of
Chapter One now draws upon the theoretical literature to present compelling reasons and recommendations for improving STEM education in the U.S. I describe the ways in which nanoscale science and technology may serve as a unifying lens to teach concepts and processes that relate to matter. Next, I discuss the idea of teacher PD as a vehicle for the improvement of STEM education and describe some limitations to the effectiveness of PD. The chapter addresses theoretical frameworks and constructs related to the study, including the key learning theories that inform this work and the construct of the metacognition principle. In the following section I describe my positionality with regard to my intended research and Project NANO. Chapter One closes with the research question and sub-questions that frame this study and a summary of the chapter.

**The Need for Reforms in STEM Education in the U.S.**

The belief articulated in the National Research Council’s (NRC) current National Science Education Standards (NRC, 1996) and the newly released Framework for K-12 Science Education (NRC, 2012) is that *every* K-12 student in the United States of America must be equitably afforded opportunities to develop a high level of scientific literacy. These documents state that high expectations for scientific literacy are essential to ensure that the next generation is better prepared to solve a plethora of social and environmental challenges, many of which may require technological and scientific solutions that have yet to be conceived (Evans, Honkapohjal & Mitra, 2009; National Science Education Standards, 1996; Rising Above the Gathering Storm Committee,
The authors of these documents argued that cultivating scientific literacy is essential for maintaining the momentum of discovery and innovation that will sustain the nation’s economic prosperity, thus protecting the nation from foreign threat, afford increased levels of equity and a higher quality of life for the citizens of our nation (Evans et al., 2009).

Science education reformers in the U.S. are acutely aware that students are operating in an increasingly knowledge-based environment that requires both instrumental and communicative learning (NRC, 2000; Oregon Education Roundtable, 2009). In order to meet the demands of living in contemporary and future society, K-12 students must be taught in such a way that supports the development of scientific literacy, including the ability to use technology to develop and communicate their understanding of complex relationships that are often interdisciplinary in nature (NRC, 2000). Indeed, the ability to operate in an increasingly complex environment means that scientific literacy has become a prerequisite for college readiness and the ability for all students to graduate and be equitably prepared to access well-paying jobs (ACT, 2010). Adults who lack the level of scientific literacy described as minimum achievement levels in the National Science Education Standards (1996) are often barred from access to many educational and professional career opportunities including jobs in STEM careers (Rising Above the Gathering Storm Committee, 2010).

Because the levels of scientific literacy in the U.S. are significantly lower for historically under-represented populations (Nord et al., 2011), this problem represents a profound social justice issue. Graduates who lack scientific literacy are less able to
contribute to the creation of policies that support a healthy environment, community, and family because they are less prepared for situations that demand logical, quantitative and qualitative data-driven decision making (Laugksch, 2000; NRC, 2012).

**Low Levels of STEM Academic Achievement in K-12 in the U.S.**

Evidence suggests that in comparison with schools in other countries, K-12 public schools in the U.S. provide less instruction that engages and inspires students in STEM learning (Johnson, Cohen, Chen, Jiang, & Zhang, 2003; Nord et al., 2011). Although reports such as the National Assessment of Educational Progress (NAEP) 2009 High School Transcripts Study (Nord et al., 2011) demonstrate an encouraging increase in the overall numbers of American high school students taking and passing more challenging courses in comparison to American students in 1990, these gains are not seen throughout the U.S. educational system. Unfortunately, over half of American racial and ethnic minority high school students are continuing to avoid taking higher-level science and math courses (Nord et al., 2011).

Figure 1 is from the 2009 NAEP High School Transcripts Study and shows that the percentage of non-white graduates who did not attain a standard curriculum by missing requirements in one or more area is significantly higher than for their white counterparts. This NAEP study shows that 52% of all black students and 50% of Hispanic students did not take higher-level science courses in high school. In comparison, 31% of all white students and 31% of all Asian/Pacific Islander students did not take higher-level science courses in high school. But the problem is not simply that students are failing to take higher-level science courses in high
International studies and statewide testing scores indicate that the academic performance of a large percentage of U.S. students in science declines the longer students remain in school (Committee on Science, Engineering, and Public Policy, 2007; Foley & Hersam, 2006). For example, in 1995 the Third International Mathematics and Science Study (Beaton, Martin, & Mullis, 1995) assessed students from 41 nations at three different grade levels (fourth, eighth, and in the final year of secondary school) to compare average levels mathematics and science achievement. The study found that at
the fourth grade, U.S. students rank above the international average in both mathematics and science. In the eighth grade, U.S. students rank above the international average in science and below the international average in mathematics. However, at the end of secondary schooling, U.S. twelfth grade students scored among the lowest of the participating nations in both science and mathematics general knowledge, outperforming only South Africa and Cyprus on both assessments (Beaton et al., 1995).

In 2009, 75% of the fifth grade students tested in the state of Oregon met or exceeded Oregon science content standards and 72% of eight graders met or exceeded the state content standards on the Oregon Assessment of Knowledge and Skills (Oregon Department of Education, 2009). However, only 58% of tenth grade students met or exceeded the science content standards. Furthermore, science and math test scores in Oregon are significantly lower for students from historically under-represented populations such as racial and ethnic minorities in comparison to their white counterparts (Oregon Department of Education, 2011). Overall, low statewide test scores provide an important indication that a large majority of Oregon high school graduates are not prepared to succeed in college-level math and science courses (Oregon Department of Education, 2011).

Social implications of low academic achievement in K-12 public schools.

Despite significant advances since 1970 in the rights of historically under-represented students to attain an equitable level of education with white students, stagnation of public investments in education over the same time period has led to only marginal improvements in the actual level of educational attainment for many students of color and
those who come from low socioeconomic backgrounds (Rise Above the Gathering Storm, Revisited, 2010). This circumstance is significant because success in math and science courses often strongly influence whether or not high school students choose to apply to college, are accepted to college and graduate (Martinez, Sher, Krull, & Wood, 2009; Roderick et al., 2008; Oregon Department of Education, 2011). As college is widely recognized as a gateway to middle class status, college attrition has become a barrier to social mobility and economic success for many people (Horn, Berger, & Carroll, 2004; United States Department of Education, 2006). The issue is becoming one of increasing concern as the earnings advantages of a college education have widened during the past 30 years (Martinez et al., 2009).

For example, the average annual starting income for someone employed full time with a bachelor’s degree in 2008 was 65% higher than for someone employed full time with only a high school degree (NCES, 2009). Over the course of a career, someone in the U.S. with a 4-year undergraduate degree can earn 75% more than a high school graduate can expect to earn, $2.1 million compared with $1.2 million respectively. Workers currently earn about 10% more money for each additional year of schooling they complete beyond high school. Even an individual with some college but no postsecondary degree can expect to earn one-third more than a high school graduate with no college experience (NCES, 2009).

College level science courses require that students enter with strong scientific literacy skills such basic science content knowledge, the ability to apply critical and analytical thinking skills to conduct scientific inquiries to make observations, draw
inferences and conclusions and to effectively communicate scientific concepts and process orally and in writing (Conley, 2007). Without a basic level of scientific literacy, entry level college science courses such as general chemistry often become barrier courses to many students, in particular a disproportionate number of students from traditionally under-represented populations (Horn & Caroll, 1998; Oregon Department of Education, 2012). Students who are not well prepared with knowledge and skills necessary to succeed in entry-level science courses may be required to take one or more remedial or developmental courses. Remedial courses do not count towards an academic degree; thus, difficulty with science course requirements cause many students to change their major to non-STEM disciplines and many more to lose heart and stop-out or drop-out of college altogether (Horn & Caroll, 1998).

As a result of these inequitable levels of educational attainment, data on the number of traditionally under-represented populations in the science and engineering workforce show that the numbers are alarmingly low (National Science Board, 2008). For example, the percentage of African-Americans in STEM related careers only grew from 2.6% in 1980 to 5.1% in 2005. Similarly, Hispanics have seen slow growth as well, growing from 2.0% to only 5.2% in that same period (National Science Board, 2008). At present, the numbers of historically underrepresented populations in the science and engineering workforce need to triple to match their share of the U.S. population (National Science Board, 2008). As it stands, many people who have the potential to make significant contributions to society are prevented from doing so due to a lack of quality preparation in school (Horn & Caroll, 1998).
Nanoscale Science and Technology: A Vehicle for Reform-Based Science Education

Partners working with the multi-institutional National Center for Learning and Teaching Nanoscale Science and Engineering (NCLT) argued that nanoscale science education has the potential to revolutionize STEM education for all students (NCLT, 2012). This claim rests on the highly interdisciplinary nature of nanoscale science, which may serve as a lens that assists learners to recognize and understand the interconnected nature of all of the STEM disciplines (Chang, 2004), which includes the various pathways within science (e.g., biology, chemistry, physics, earth and space science). Research (e.g., Roco, 2003) demonstrates that the study of science as interconnected disciplines produces strong student understanding of the core unifying scientific concepts set forth in the National Science Education Standards (NRC, 1996) and the NSTA Framework for K-12 Science Education (NRC, 2012).

The introduction of nanoscale science and technology in the classroom provides an interdisciplinary framework within highly disjointed curricula that most often presents scientific knowledge as entirely separate concepts and processes (NCLT, 2012). Nanoscale science bridges concepts from the STEM disciplines of physics, biology, chemistry, materials science, mathematics, engineering and medicine by providing authentic examples of science in action. Indeed, it is difficult to find a context in society that is not somehow affected by nanoscale science and technology (Stevens, Sutherland, Schank, & Krajcik, 2007). Nanoscale science and technology is revolutionizing computing, medicine, materials science, energy production and manufacturing (Roco,
From the rain repellent layer on raincoats, to the chips in the cell phones we communicate with, to diagnostics used to ensure that the produce and meat we buy in the grocery store do not contain dangerous viruses and bacteria, we are surrounded by and enormously benefit from this new capability to observe and manipulate molecules at the atomic scale (Hsi, Sabelli, Krajcik, Tinker & Ellenbogan, 2011).

Work done by Stevens, Sutherland, Krajcik (2007), Xie and Pallant (2010) and other early researchers (e.g., members of the National Center for Learning and Teaching in Nanoscale Science and Engineering) in the field of nanoscale science and technology education find that viewing images at the nanoscale helps students to develop the ability to use higher order thinking skills such as critical thinking, problem solving and the ability to think abstractly in the process of doing science through experimentation,

For a tool to be more educational, students should be allowed to “mess around” with models, try many hypothetical experiments, and see what happens. It is during iterations of this type of experimentation that students learn progressively and become inspired. (Sweeney & Seal, 2008, p. 4)

Using nanoscale models and simulations and microscopes, students have the opportunity to examine materials and learn about the benefits of detecting structural patterns at various scales. For example, students may gain an understanding of the science of biomimicry by doing things like examining the rain repellent characteristics of the leaves of certain plants in comparison to nanoscale rain repellent substances applied to raincoats (Biomimicry 3.8 website, 2012). Such an active inquiry process related to practical, familiar applications of science functions to improve students’ comprehension of big ideas in STEM and how these ideas inter-relate (NCLT, 2012).
For students who are struggling with the challenge of learning English or have learning disabilities, contextual understanding may make an enormous difference to their ability to successfully approach learning complex scientific concepts. Units of instruction that draw upon familiar examples of applications of nanoscale science and technology in everyday life may serve to engage all learners, even students who do not see themselves as being good at science or have struggled in science classes in the past (Sweeney & Seal, 2008). Understanding how nanoscale science is applied in the world they live in may move students’ understanding from thinking of the discipline of science as one of memorizing facts and formulas to understanding how facts, formulas and other tools are applied to create solutions and to further our understanding of the natural world and how it works.

The Call for Inclusion of Nanoscale Science and Technology in Secondary Education

Because of the great potential for using nanoscale themes as one approach to interdisciplinary instruction, calls to include nanoscale experiences in secondary level education are being made from a variety of stakeholders such as members of industry, government, civic organizations, scientists and engineers, technology educators, and social scientists (Brune et. al., 2006; European Commission, 2010; Healy, 2009; Roberts, 2004; Roco, 2003). Advocates claim nanoscale science and technology provides a useful backdrop for students to engage in scientific inquiries, which draw on themes that are interesting and relevant to the lives of many students (Roco, 2003). For example, high school students involved in a Project NANO chemistry lesson on percent of compositions examined the ingredients in green eye shadow and the potential effects of the ingredients
found in the make-up on the human body (M. Blok, personal communication, March 13, 2012). The students in the class reported to their teacher that they felt highly motivated to investigate the percent composition of the ingredients found in the make-up using the microscopes rather than trusting claims made by the manufacturer. The students said that they felt inspired to examine the make-up because they put the make-up around their eyes and they felt compelled to learn what is in the make-up and what some effects of the minerals in the make-up on their bodies might be, such as potential allergies caused by the filler bismuth oxychloride and the minerals such as mica used to give eye shadow its color.

**Rationale for the Importance of Nanoscale Science and Technology in Secondary Curricula**

In a review of the scholarly literature, Hingant and Albe (2010) found three main arguments for the inclusion of nanoscale science and technology in the secondary science curriculum. The most frequent argument has to do with the need to adequately prepare a domestic workforce to ensure that the United States is well positioned to meet the growing demand for highly skilled technicians, engineers and scientists in the field of nanoscale science and engineering (Foley & Hersam, 2006). This literature typically situates the discussion within the context of the concern that the current system of education in the U.S. is not equipped to meet this goal.

According to an essay entitled, “Can Nanoscience Be a Catalyst for Educational Reform?” which appears in the *Anthology of Nanoethics Essays* (Roco, 2003), “It is estimated that two million people with knowledge of nanoscience will be needed to work in a variety of professions worldwide by the year 2015” (p. 1247). A major concern of the
National Science Foundation and the National Nanotechnology Initiative is that the United States will not have the workforce or intellectual capacity to compete worldwide in nanoscience efforts (Nano.gov, 2012).

The second argument, tied directly to the first, is founded on the belief that it is a matter of national interest to ensure that our students are adequately prepared to compete economically with foreign nations, particularly those in Asia, to conduct nanoscale science and engineering research and development here in the U.S. (Foley & Hersam, 2006). Proponents of this argument state that it is, …the responsibility of national, state, and local education leadership in the United States to prepare a much larger cross-section of the U.S. population with the science and engineering knowledge necessary to function in a highly technological society and to maintain the momentum of discovery and innovation that will sustain the nation’s economic prosperity. (Roco, 2003, p. 1)

Once again, this argument situates the discussion within the context of the concern that the current system of education in the U.S. is not equipped to meet this goal of maintaining a competitive edge in nanoscience research and development in the world.

This argument relates to a third most frequently cited concern found in the literature, which is the need to develop a highly scientific literate populace particularly well equipped in terms of “nano-literacy in order to navigate some of the important science-based issues related to everyday lives” (Laherto, 2010, p. 161). As is the case of the first two arguments, this literature typically situates the discussion within the context of the concern that the current system of education in the U.S. is not adequately preparing all students to fully take advantage of the science and technology currently available to them. Without an adequate level of scientific literacy, graduates of the U.S. educational
system may be ill-equipped to contribute to the development of solutions to serious challenges faced by the current and rising generations, some of which may be strategies to address problems we do not yet know that we have (Roco, 2003; Laherto, 2010).

Unfortunately the expense of nano-tools, the lack of nanoscale science curriculum and the very small number of established nanoscale science and technology teacher PD models are slowing down the process of including nanoscale science and technology into K-12 schools (Bryan et al., 2007). According to the National Center for Teaching and Learning at the Nanoscale (NCLT), although there are currently a wide variety of nano-tools available to professional researchers, very little nanoscale technology has been made available for secondary level students and teachers to actually manipulate nanoscale microscopes as a learning tool used to study and manipulate matter at the level of molecules and cluster of molecules (Laherto, 2010; NCLT, 2012).

The recent development of relatively inexpensive nanoscale instruments such as the table-top scanning electron microscope means that new technology has begun to be available to students, instructors and researchers at the university level in the U.S. However, unless a high school student is lucky enough to gain access to university labs through an internship or a dual credit course, the average student does not have the opportunity to learn using nanoscale technology (Bryan et al., 2007; NCLT, 2012).

This lack of accessibility at the secondary level of education has broad societal, economic and ethical implications (Bryan et al., 2007; Nano.gov, 2012). For example, the most commonly heard refrain for the importance of integrating nanoscale science and technology into K-12 education estimates that the worldwide workforce necessary to
support the rapidly expanding field of nanoscale science and technology will be close to two million by 2015 (The Nanotechnology Initiative, 2007; Sabelli et al., 2005; Stevens, Delgado, & Krajcik, 2010; Zenner & Crone, 2008). If the educational system in the U.S. fails to equip high school graduates with skills and knowledge necessary to be college ready so that graduates will be competitive for jobs as researchers, engineers, and other professional specializations in nanoscale science and technology, companies will be forced to look elsewhere for qualified workers (Laherto, 2010; Nano.gov, 2012).

Rationale for the Need to Develop Nanoscale Science and Technology

Teacher Professional Development Models. Given that nanoscale science and technology is viewed by the National Science Foundation as the anchor for the next industrial revolution (Hingant & Albe, 2010; The National Nanoscience Initiative, 2007), experts have expressed grave concern that American students are falling behind in the essential subjects of math and science, putting our position in the global economy at serious risk, a strong argument for providing quality teacher PD that successfully assists teachers to improve their practice (Sweeney & Seal, 2008).

One of the reasons that U.S. students struggle in math and science is a lack of adequate teacher preparation to teach foundational concepts let alone teach using the latest strategies that often include an interdisciplinary approach to understanding concepts and processes. Nationwide, approximately a third of high school math students and two-thirds of students enrolled in physical sciences classes have teachers who did not major in math or science in college or are not certified to teach science (National Math and Science Initiative, 2012). Students attending schools in low socio-economic areas with a
high level of ethnic diversity are even more likely to have teachers who lack a science subject endorsement (Darling-Hammond & Baratz-Snowden, 2007). Even in the case of those who did major in a scientific discipline, given that secondary science teachers usually major in college in one discipline (e.g., biology, chemistry, physics, ecology, anatomy and physiology, earth and space science) even scientifically trained teachers lack deep content knowledge necessary to develop interdisciplinary units of instruction (Schank et al., 2007). In addition to a lack of adequate preparation and on-going support to teach leading edge science, many teachers also lack technical knowledge to effectively integrate scientific digital tools into the curriculum (NEA, 2006).

Unfortunately, teachers’ lack of preparedness to effectively integrate technology as a learning tool into the curriculum is not limited to novel digital technology such as nano tools. In a 2008 National Education Association survey of nearly 2,000 classroom teachers and teaching assistants, researchers found that 60% of teachers reported that their districts required technology training, and most felt competent in using technology for administrative or communications purposes. However, fewer than half felt their training for using technology directly with students was adequate. These findings were reflected in teachers’ reports of how they actually used technology in their classrooms. Although 76% of teachers reported using technology for administrative purposes on a daily basis, fewer than half of teachers used technology daily to monitor student progress (41%), for research and information (37%), to instruct students (32%), and to plan and prepare instruction (29%). In addition, teachers in urban schools were less likely than
those in suburban and rural/small town schools to use computers on a daily basis for both administrative and instructional tasks (NEA, 2006).

So although evidence exists for the need to develop quality teacher PD to assist teachers with learning new content knowledge, technological and pedagogical skills, there is no silver bullet to define how to best design nanoscale science related teacher PD. In recognition of the need to produce a variety of approaches to develop human capacity in nanoscale science and engineering by providing teachers with support, the U.S. government and nations such as India, the United Kingdom, China and Israel are creating multiple initiatives to rectify problems created by the ineffectiveness of the current science education system (e.g., Sabelli et al., 2005; Stevens et al., 2009; Stevens et al., 2010; Zenner & Crone, 2008).

For example, in the U.S., the National Science Foundation (NSF) and faculty researchers with NCLT recognize that for teachers to be empowered to figure out how to effectively integrate nanoscale science and technology within the existing corpus of scientific knowledge they are required to teach, they need to understand what big ideas transcend the boundaries of traditional scientific disciplines. In response to this perceived need, the NSF sponsored a series of workshops and studies to establish nine big ideas in nanoscale science. These nine big ideas are: size and scale; structure of matter; forces and interactions; quantum effects; size-dependent properties; self-assembly; tools and instrumentation, models and simulations; and science, technology and society (Sabelli et al., 2005; Schank et al., 2007; Stevens et al., 2009; Stevens et al., 2010).
It could rightly be said that these nine big ideas in nanoscale science are some of the big ideas of all science as defined in the U.S. (AAAS, 1993). Indeed, the broad-reaching, interdisciplinary nature of nanoscale science provides the opportunity to remove artificial constructs that serve to separate the scientific disciplines in order to address unifying and cross-cutting concepts by drawing on a multitude of disciplines. According to members of the NCLT, these big ideas provide a “foundation for building coherence into the science curriculum” (Stevens et al., 2009, p. xiv).

However, most current science curriculum is not designed using a multi-disciplinary scientific approach to knowing, which means that until new curricula are fully developed and tested, it is up to teachers to learn and know scientific concepts and a wide menu of teaching strategies well enough to be able to draw upon interdisciplinary scientific perspectives to weave novel science content and technology into existing curricular materials. Admittedly, even once curricula have been fully developed, it will still be up to teachers to know how to best draw upon and adapt materials to fit coherently within their courses to suit the needs of their particular students. To assist with this effort, the NCLT’s NanoEd Resource Portal Website, Stanford University’s Stanford Research Institute (SRI) International Nano Sense project website and the Case University’s Nanopedia Project offer pedagogical resources on-line to support teacher and student learning. However, to be effective, web-based resources need to be augmented with professional development support for teachers who have very little time to learn and internalize new content while maintaining their classroom responsibilities (Erstad, 2006; Shank et al., 2007; Tomasik et al., 2009; Wilson, 1998).
The National Center for Teaching and Learning in Nanoscale Science and Engineering (NCLT) is working to bridge this gap of teachers’ knowledge and skills by providing websites offering nanoscale science and engineering information that includes sample lesson plans, readings for students, nanoscale photo micrographs and other online resources intended to help teachers to more effectively situate nanoscale science and technology within the curriculum (Healy, 2009). These materials provide examples meant to help educators and learners understand that observation and manipulation of matter at the atomic scale involves ideas in science crossing the traditional bounds of scientific disciplines and that there are a multitude of strategies available to frame learning these ideas (Stevens et al., 2007).

However, simply offering resources on-line or elsewhere does not adequately support most teachers to the degree that they are able to build upon the curricula materials available in a way that meets state content standards. Nor do online resources necessarily help teachers to figure out how to fit new content and technology with existing curricula to meet the needs of their particular students (Schank et al., 2007; Tomasik et al., 2009). Thus, I turn now to a more general discussion of teachers’ PD and learning that informs the design and exploration of effective PD in nanoscience for secondary teachers.

**Teacher Professional Development**

Continuous education and support is an integral part of any profession. Teaching is no exception. The Next Generation Science Standards (Achieve, 2013) inclusion of new science and technology impose an ever-increasing set of expectations for how and
what students will learn in the STEM disciplines. Teacher PD is a necessary feature to implement educational reform across the disciplines of science (NRC, 2012).

According to principles of learning described in books such as *How People Learn* (NRC, 2000) and *How Students Learn* (2005), research indicates that to improve student learning, teachers must move towards a more balanced approach that emphasizes a deep understanding of subject matter by students (Cohen, McLaughlin, & Talbert, 1993; Darling-Hammond & McLaughlin 1995; NRC, 2012; Porter & Brophy, 1988). To accomplish this goal, teachers must learn more about the subjects they teach, how students learn these subjects and how to adapt instruction to meet the very specific needs of students (Loucks-Horsley et al., 1998; National Board for Professional Teaching Standards, 1989; National Commission on Teaching and America’s Future, 1996; Shulman & Sparks, 1992).

A wide variety of models of teacher PD intend to improve teacher’s content knowledge, instructional strategies and ability to utilize technology to enhance classroom instruction (Darling-Hammond, Wei, Andree, Richardson, & Orphanos, 2009). However, not all experiences are created equal. Regardless of whether the PD is in the form of a retreat, workshop, university course, job-embedded experiences or otherwise, participants in the 2001 study conducted by Garet, Porter, Desimone, Birmann, and Yoon said that effective PD explicitly supports teachers to find opportunities to fit newly introduced technology and content coherently into the curriculum and classroom environment. Furthermore, effective PD goes beyond teaching content and pedagogical knowledge. Effective PD also addresses PCK by providing a selection of effective instructional
strategies and importantly, a rationale for why particular strategies may be most likely to have successful impacts on student learning within a given context (Garet et. al., 2001).

In a study entitled *What Makes Professional Development Effective? Results from a National Sample of Teachers* (Garet, Porter, Desimone, Birman, & Yoon, 2001), researchers found some common denominators of high quality teacher PD. In response to this and other studies, the National Staff Development Council (NSDC), Learning Forward program with the help of more than 40 other educational organizations developed the third iteration of Standards for Professional Development (2011), which I describe in greater detail in Chapter Two. This set of Standards for Professional Development state that effective teacher PD is sustained and intensive (at least 30 hours plus follow-up academic-year support), focuses on academic subject matter (content), and provides teachers with opportunities for collaborative, active learning of content and teaching strategies (Darling-Hammond & McLaughlin, 1995, 2005; NSDC, 2012).

**Theoretical Framework Relating to Learning**

Project NANO and this dissertation study are rooted in contemporary and time-honored research on how people learn as well as in research on design principles for professional development. Situated cognition and social constructivism are the key learning theories that guide Project NANO and this research, based as they are on decades of research on cognition and factors that influence how people learn.

**Situated Cognition.** The theory of situated cognition (Lave & Wenger, 1991) states that social interaction impacts learning as much as individual expenditure of mental
effort. In this case, the term *social* refers not only to other persons but also to that which has been created by people. Lemke summarized that:

> Learning is always bound up with, co-dependent with, the participation and activity of others, be they persons, tools, symbols, processes or things. How we participate, what practices we come to engage in, is a function of the whole community ecology, or at least of those parts of it with which we join in with. (Lemke, 1997, p. 189)

For many people, learning takes place within the context of a social environment in which observational learning becomes a critical tool useful for trying out new ideas, testing the logic of these ideas and either refuting or incorporating these ideas (von Glasersfeld, 1989a, 1996). Collins (1988) defined situated learning as the notion of learning skills and knowledge in contexts that reflect the way they will be used in real life. Thus, situated cognition theory encourages educators to immerse learners in an environment that approximates as closely as possible contexts in which their new ideas and behaviors will be applied (Schell & Black, 1997).

**Social Constructivism.** As a type of constructivism, social constructivism holds that learners are not blank slates when they enter our science classrooms. Learners at all levels bring with them experiences where they have made observations, developed interpretations and formed opinions on which to base their beliefs and opinions (von Glasersfeld, 1992). These experiences form the basis for how people collaborate to interpret new information and either incorporate information into their knowledge structures or draw upon new information to test previous interpretations (NRC, 2000). For the social constructivist, learning is a generative process of social cognition through
which people work together to build new understandings of concepts, processes or ideas for themselves (von Glasersfeld, 1992).

Although there is indeed significant overlap between social constructivism and social learning theory, there are distinctive characteristics of each theory. Social learning theory is focused on the internal knowledge structure or cognitive functions of the individual learner as evidenced by behavior (Bandura, 1977). This theory represents a departure from ideas related to the theory of behaviorism and the idea of operant conditioning. Social learning theory is concerned with examining cognitive psychology to explain role of social interactivity in the development an individual’s sense of confidence, motivation, repetition, and emotional support in relation to behavioral development. Social constructivism is also focused on the role of interactivity in learning; however in this case, the theory emphasizes the tools provided by culture that assist a learner in building upon current and prior knowledge. For example, the idea of the zone of proximal development emphasizes the influence of cultural history, social context, and language on assisting students with the task of learning which they otherwise may not be able to do by themselves (Vygotsky, 1934). In contrast to the individual-cognitive constructivist, the socio-cultural constructivist locates the mind in the individual-in-social-action. Therefore, learning is primarily a process of enculturation into a community of practice (Lave & Wenger, 1998).

**Learning progressions.** To think about science teachers’ learning progressions is to think about how ideas and skills for teaching become refined over time. As educators acquire teaching experience over time, they gain skills and knowledge for how to best
frame science instruction. In the process of reflecting on what they know and learn about how to teach science, experiences contribute to the development of increasingly sophisticated approaches to adapting learning experiences to meet the needs of diverse learners. Career-long support is necessary to support teachers to consciously consider how new scientific concepts and technology fit within their own body of knowledge and how new ideas may be applied to change teaching and learning practices.

The construct of learning progressions fits neatly with Wiggins and McTighe’s (2006) argument that for learning experiences to be successful, clear objectives must be identified so that learners understand what they will know and be able to do as a result of an educational experience. The ability to establish clear learning objectives depends on the teachers' own depth of content knowledge and technical skills. A hallmark of an expert teacher is the willingness to approach new teaching and learning challenges from the perspective of an intelligent novice who often struggles as they learn new things (Bransford, 2001).

Another hallmark of expert teaching is to know content well enough to flexibly frame educational experiences for students in multiple ways in anticipation of individual needs while also maintaining the ability to efficiently serve the needs of the entire group (Darling-Hammond, 1996). Although each individual approaches challenges associated with learning and teaching new content and skills from different entry points, each teacher experiences a series of progressions in the process of becoming increasingly sophisticated in defining clear learning objectives and facilitating learning for diverse populations of students.
Although the construct of learning progressions is perhaps most appropriately applied to considering career-long learning trajectories, this construct is useful for this study as one of several lenses applied to interpret how teachers’ learning progresses in the increasingly common situation wherein educators are asked to negotiate the inclusion of novel science and technology into the curriculum. Although this study examined teachers in the first year as they approached learning nanoscale concepts and implementing a new nanoscale science unit for the first time, this study contributes to efforts to begin to fill critical gaps in what is known about how teachers think and learn during the initial stages of implementation. These data will contribute to inform the design of teacher professional development opportunities and to ideas for how to assess teacher learning (Wilson, Floden, & Ferrini-Mundy, 2001). This study represents a necessary foundational step in establishing baseline knowledge of teachers' learning progressions related to the introduction of any novel science content and technology.

**Reflection/Metacognition Principle**

In addition to the learning theories, the construct of metacognition is an important idea that frames this study. Metacognition, or thinking about one’s own thinking, is a critical component of learning (von Glasersfeld, 1992). Metacognition consists of two mental processes: monitoring and responding (Flavell, 1976; Sternberg, 1998). Monitoring includes checking in on one’s own process of learning and thinking about how new information fits with the old; responding refers to tracking feedback and deciding to continue with an old belief, to make changes to a previously held
understanding, or to adapt one’s perception as necessary and then, act upon this new awareness (Flavell, Speer, Green, & August, 1981; Novak, 1985).

Because learning is grounded in a set of ideas including values and beliefs, reflection entails a critical examination of not only rational thoughts but also of one’s values and beliefs and how those influence how one perceives information (Mouza, 2006; Zohar, 2006). However, for the purposes of this study, I did not explicitly examine teachers’ beliefs and values that inform their choices of strategies, as important as they are.

This study addresses a sub-component of teachers’ metacognition that Zohar (2006) referred to as *metastrategic knowledge*, or explicit knowledge of the cognitive procedures used by the teacher to facilitate students’ understanding of how to approach learning specific topics,

… it consists of the following abilities: making generalizations and drawing rules regarding a thinking strategy; explaining when, why and how such a thinking strategy should be used, when it should not be used, what the disadvantages are of not using appropriate strategies, and what task characteristics call for the use of the strategy. (Zohar, 2006, p. 337)

Although metastrategic thinking may refer to both the teacher and the learners’ cognitive processes, this study is specifically focused on examining and describing teachers’ metastrategic thinking that inform their teaching strategies.

Operating within a group of teachers around problematized tasks provides teachers with the opportunity draw upon metastrategic thinking to build upon their PCK related to teaching specific topics as they test and refine ideas in a low stakes environment in preparation for working with students. Such an experience assists
teachers in developing the ability to anticipate how students may respond to particular activities (Clermont, Borko, & Krajcik, 1994; Mouza, 2006).

For example, in the Project NANO summer workshop groups of teachers developed scientific inquiries related to working with specific samples. They experimented with various materials to see how things like snake skin and hair image in an SEM. Through observation and conversation, they learned that the oil in snake skin causes the sample to consistently image poorly whereas there was a range of image quality for samples of hair taken from different animals. They developed a catalogue of samples that image well, recorded and shared the optimal range of magnification for various samples and noted samples that are difficult or impossible to image. They collaborated to determine how to narrow the range of investigations to frame the instructional units they developed based on their new understanding of how to increase the level of student success. By drawing on this PCK, teachers were able to better employ their metastrategic thinking to plan strategies that would ensure that students remain more focused on learning the actual objectives in the lesson rather than focusing too much on negotiating the use of the instrument instead.

Teachers involved in lab groups also developed PCK related to thinking about how to tailor the unit to meet the specific developmental needs of their students. With guidance from A Framework for K-12 Science Education (NRC, 2012), Oregon science content standards and content knowledge developed with their lab partner, each teacher drew upon their PCK to tailor the unit to suit the developmental level of the particular grade he or she teaches.
For example, a seventh grade science teacher and a high school teacher partnered to design a forensic science unit of instruction involving a cyclical rotation of lab stations with instruments used to examine evidence to investigate a crime scene. The final product that each teacher refined after the conclusion of the workshop differed in several important ways.

The primary focus of the seventh grade teachers’ final forensic science unit was on facilitating student development of specific cognitive and practical skills such as observation and understanding how to apply protocols and procedures of science to investigate crime scene evidence. The seventh grade teacher’s unit dedicated a large portion of time to activities exploring size and scale, as well as to modeling how to use specific scientific instruments and engaging students in discussions to help them develop language to characterize evidence and formulate hypotheses.

The final unit designed by the high school teacher assumes that the students in the class have developed these foundational scientific cognitive and practical skills prior to coming to her class. So the unit she designed builds upon these skills. The high school teacher’s metastrategic approach was to design a unit that engages students in determining the correct instrumentation to use to examine various materials, optimize the use of microscopes and data analysis software, accurately recording observations and building a body of evidence to support a claim. The high school level unit places an emphasis on scientific argumentation involving the use of quantitative and qualitative reasoning employed to justify the interpretation of the evidence presented to justify a knowledge claim. Thus, the seventh grade teacher’s final unit and the high school level
unit differed in that they involved content and skills that were intentionally scaffolded along an increasingly sophisticated learning progression.

Heretofore I have described the context and problem that frames this study. In the next section, I transition into a description of my own positionality as a researcher engaged in this dissertation research.

My Positionality

As a child I had the luxury of growing up on the edge of the Tahoe National Forest in California. When my mother told us to go outside and play, we wandered with our own purpose for hours on end in the forest that was our backyard. I thought that I knew every tree, every trail, and every stream by heart. The experience of growing up as one creature among many who lived in that forest imbued in me an understanding of my life as part of a connected whole in nature. Someone standing at the front of a room lecturing about the natural world with overhead images and dry erase markers could have never communicated what childhood experiences taught me about the importance of viewing life within the context of the greater whole.

In my early 20s I began working with K-12 teachers as a project-based learning coordinator. For the next 12 years, nearly every project I collaborated on with students and teachers had a scientific component to it that fostered children’s natural sense of wonder. Throughout this period I drew heavily on my own memories of what it was like to ask questions about things I knew and cared about. I thought about how adults gently guided my explorations and helped me to learn ways to seek out understanding the natural and the built world. I shared my playful approach to doing science with children.
and teachers as a way to keep our natural curiosity and passion to learn alive and growing in our community of explorers.

As teachers and I worked together, we found that our ability to communicate and trust each other improved over time. We let down our guard a bit about exposing our ignorance to one another because we had an immediate, practical need to figure out our own scientific questions together and think beyond the bag-of-tricks mentality to figure how to scaffold activities using instructional strategies that would be most likely to engage higher levels of thinking for each student and group of students. The opportunity to reflect together on what we observed about student thinking informed the choices we made throughout lessons. We made the conscious decision to keep our learning objectives up front and to not be too tightly wedded to our lesson plans if the cues we observed coming from the children took us in a different direction to address important learning objectives.

For example, if we planned to go to the forest with children to draw the parts of plants but the kids excitedly circled around an interesting flower to discuss what they noticed and wondered about the parts of the plants, we realized that they were developing their ability to characterize the parts of the plant using verbal and visual cues rather than written cues as a preliminary step to being able to make observations on their own to draw what they saw. It was acceptable if we ran out of time on our forest walk and needed to have them draw pictures of the flowers from hand samples placed on their desk at school because the primary learning objectives were still addressed. Careful observation of our students themselves helped us to figure out how to meet the challenge
of recognizing and changing some of our outdated, ineffectual practices including ideas about classroom management and use of time. As we noticed the students’ growing ability to partner within a community of explorers to direct their own learning based on ideas they cared about and could relate to, we became excited and confident about trying out new ways to approach teaching content and reflexive ways of working with the students.

My concept of the community of practice I operated within expanded and continues to nurture my learning as an learner and an educator. I continue to recognize an ever-widening community of practice that includes educators, students, parents and classroom volunteers as essential to the development of my own PCK knowledge as Shulman (1986, 1987) has described this construct.

The collaborative experience of working intensely with four to five teachers per year was immensely satisfying to me because I love working directly with teachers and students and because my learning curve was in a steep upward slope nearly every day. But like many who have tread the path of a K-12 support staff person, I began to feel frustrated that I was not able to help more teachers and students each year. So seven years ago, I chose to move on to work at the university level where I could support the growth and development of many more teachers each year working as a science teacher PD program coordinator, program evaluator, researcher and instructor.

Out of all of the science teacher PD that I have had the honor to work with, I chose to focus my dissertation study on Project NANO because of my interest in teachers’ PCK and the novel science and technology aspect of the program. I currently
serve as the internal evaluator of Project NANO under a grant from the M.J. Murdock Charitable Trust with in-kind funding support from Phenom World NA, Inc. and a local university. I discuss my role as the evaluator and its relation to my role researcher of this dissertation inquiry in Chapter Three.

**Research Questions and Approach**

The research question that framed this study are: *How do teacher participants in the 2012 Project Nanoscience and Nanotechnology Outreach (NANO) program negotiate the inclusion of novel science and novel technology into the science curriculum?*

There were three sub-questions:

1. Do teachers demonstrate scientific content knowledge gains in response to the 2012 Project NANO summer workshop?
2. Of the nine “big ideas” in nanoscale science and technology, which are the big ideas that teachers choose to teach in their Project NANO unit and why?
3. How, if at all, do teachers metastrategic thinking and PCK change between the beginning of the summer workshop and the reflection period following the implementation of the Project NANO unit?

This descriptive case study examined how teachers drew on what they learn in the Project NANO workshop, their metastrategic thinking and their PCK to negotiate the inclusion of nanoscale science and technology into their science classrooms. This research approach was designed to provide opportunities for teacher participants to reflect in writing and verbally on, for instance, what they know about student thinking and scientific content to inform lesson design including the choices of teaching strategies suitable for particular groups of students. The study examined how teachers’ lessons evolved throughout the units of instruction in response to the reality of the classroom.
Given that the Next Generation Science Standards (Achieve, 2013) include nanoscale science concepts, data generated through this study provide useful knowledge for other teachers, researchers and PD providers faced with the challenge of negotiating the inclusion of nanoscale technologies and concepts within the corpus of science topics that each teacher in this country is required to teach. This designed-based approach to research also provide valuable information for Project NANO workshop instructors and coaches to reflect on the elements of the program that appear to effectively support teacher learning. Feedback from teachers also point to areas that need improvement in the overall program.

The term *negotiate* here refers to the metastrategic thinking process that a teacher undertakes throughout planning and teaching each lesson to recognize the best options for effectively facilitating the development of student understanding. This negotiation is informed by each teacher’s knowledge of content, instructional strategies, curriculum, assessment, student thinking and awareness of the nuances of the social context in which learning is taking place (Kuhn, Black, Keselman & Kaplan, 2000) in a word, their PCK.

For example, teachers involved in Project NANO engage in a recursive task of first learning how electron microscopes (SEM) work scientifically, how to operate an SEM and then choose the most appropriate topics to teach using the instrument. Teachers are asked to consider integrating the SEM into units of instruction that address topics that are typically difficult for students to comprehend that may be easier to grasp if they have the opportunity to examine specimens at various scales using an optical and electron microscope. To do this, teachers must figure out how to logically fit the Project NANO
unit into the larger lesson cycle of the course in a way that makes explicit sense to both
themselves and to students. Throughout this process, teachers negotiate meaning and
logical fit between the content, technical skills and knowledge, the curriculum and what
they know about how students think and learn.

This negotiation is not a linear process. Instead negotiating the inclusion of novel
content and technology is informed by the process of developing strategies for
recognizing student success and struggles, pre-planning activities in anticipation of
barriers to learning and developing back-up plans in advance and on the spot as a
reflexive practice. Indeed, each teacher’s process of negotiation may in fact be distinctly
different depending upon his or her own experience and context. If this were not the case,
than simply scripting one common curriculum with no accompanying teacher PD would
be sufficient to do the job of helping teachers with this task of integration of novel
science concepts and technology. However, I believe that scripted or unscripted
curriculum alone is not sufficient for assisting teachers in figuring out how to articulate
new content and technology into curriculum.

I focused on the process of how teachers negotiate the inclusion of new content
and technology into curriculum based on the belief that science curriculum is not a recipe
or a compendium of how information should be taught at a particular grade level. Rather,
curriculum materials support teachers in making better, more thoughtful, informed
decisions about their students’ scientific learning experiences by providing a coherent
framework for how to introduce and engage with concepts and processes found in the
natural and built world (Loughran et al., 2008).
For the purposes of this study, the term *novel* shall be defined to mean information or technology that is of recent origin that is unusual, strange and possibly surprising (Merriam–Webster Dictionary, 2012). Novel science and technology implies that a concept or tool is innovative, unusual or breaking fresh ground. The legal application of the term novel most often refers to an amendment to an existing statute. This concept of amending previous knowledge works well in reference to novel science or technology in that novel information or perspectives on information may redefine early conceptions and contribute to new applications of existing technology. For example, microscopy itself is not new, however the use of electrons in a digital microscope to magnify an object rather than photons or light reflecting off of mirrors in an optical microscope is a novel application of microscopy.

**Summary**

In Chapter One, I laid out the importance of scientific literacy to individuals and society and problems stemming from low levels of student achievement in K-12 STEM education. The need for reform in STEM education has implications related to economic progress and social justice for all U.S. citizens as well as profound environmental opportunities and challenges that face every living being on Earth. Indeed, it is difficult to overstate the importance of providing quality education to the next generation of students to empower them to solve significant problems, some of which we do not even know that we have yet.

Teacher PD is a major vehicle for STEM education reform and of educational reform in general. The need to provide quality STEM education prompts efforts to create
improved models of science teacher PD that align with the national teacher PD standards described in the Learning Forward initiative (NSDC, 2012). By its very nature, nanoscale science has great potential as a vehicle to shift science education to a more interdisciplinary approach to explore natural phenomena. This descriptive case study contributes to the development of quality teacher PD in the sciences by examining and describing teachers’ metastrategic thinking and PCK used to learn novel content and technology and used to negotiate the inclusion of nanoscale science into the curriculum. In Chapter Two, I build upon many of the ideas described in Chapter One with presentation literature that informed this study.
CHAPTER TWO

A REVIEW OF THE LITERATURE

Whereas in Chapter One I described the theoretical foundations of this study, in Chapter Two I present a review of empirical literature with some references to theoretical literature as necessary to frame the context of the study. The chapter begins with a presentation of literature that provides the rationale for reforms in STEM education. Five bodies of research comprise the empirical foundation for this study. This contemporary scholarship focuses on research on metastrategic knowledge, PCK, learning progressions, content-based teacher PD as a context for developing both content knowledge and PCK, and teacher learning.

In Chapter Two, I pay particular attention to the importance of scientific literacy and the role of scientific inquiry as a vehicle for quality science education and education reform. Next, I provide a rationale for the importance of nanoscale science and technology in grades 6-12. What follows is a review of literature that defines teacher PD, describes various approaches to supporting teacher learning and dimensions that characterize effective PD described in the empirical literature. The chapter concludes with a further description of adult learning theories as they relate to social constructivism and situated learning. This section describes how adult theories are central to an effective content-based teacher PD and relate these ideas to two key constructs that frames this study, metastrategic thinking and PCK.
Rationale for the Importance of STEM Education Reform

The National Science Education Standards, published by the NRC in 1996 and the Framework for K-12 Science Education (NRC, 2012) present a strong case for the importance of science literacy for all Americans. The National Science Education Standards make the claim that:

…in a world filled with products of scientific inquiry, everyone needs to use scientific information to make choices that arise every day. Everyone needs to be able to engage intelligently in public discourse and debate about important issues of science and technology. Furthermore, everyone deserves to share in the excitement and personal fulfillment that come for understanding and learning about the natural world. (NRC, 1996, p. 1)

A primary purpose of the current National Science Education Standards and the newly revised Next Generation Science Standards (Achieve, 2013) is to provide a vision of a scientifically literate populace.

The academic community has long debated the definition of the term scientific literacy, an issue that may have played a role in the delay in achieving a highly scientifically literate citizenry in this country (American Association for the Advancement of the Sciences [AAAS], 1989). In an attempt to bring clarity and progress through a reform effort entitled Project 2061, the AAAS released two books entitled Science for All Americans (1989) and Benchmarks for Scientific Literacy (1993). These texts, which align with the National Science Education Standards (1996), are intended to, “spell out the knowledge, skills and attitudes all students should acquire to become a scientifically literate citizen” (AAAS, 1989, p. 3) and to inform teacher PD efforts to support educators to implement science standards.
Science for All Americans (AAAS, 1989) and Benchmarks for Science Literacy (1993) have described “habits of mind” (AAAS, 1989, p. 133) that enable scientifically literate citizens to develop a scientific worldview that empowers people to,

…deal sensibly with problems that often involve evidence, quantitative considerations, logical arguments, and uncertainty…not only with respect to decisions involving their own lives but also with respect to issues that affect societies in general (e.g., assessing the use of new technologies and their implications for the environment and culture). (AAAS, 1989, p. 13)

These habits of mind involve the development of critical thinking skills such as the ability to apply reason to problem solve and drawing upon empirical evidence to make and defend a claim.

To support the development of a scientific worldview, Project 2061 recommends that teachers transcend the traditional boundaries between the disciplines by drawing on common themes such as systems, patterns of change and scale (AAAS, 1989) to demonstrate the connected nature of the STEM disciplines (Roco, 2003). Based on the recommendations from Project 2061, the Next Generation Science Standards released in April of 2013 refer to these overarching themes as unifying concepts with cross-cutting themes. Examples of unifying concepts include the ideas of evolution of life and biological adaptations. To understand the mechanisms that have shaped the evolutionary adaptations of organisms, one must understand something about natural selection and genetics, the effects of environmental pressures on genetic mutations, and the effects of life on the environment. These topics draw upon content from the disciplines of biology, ecology, geography, geology and chemistry and potentially other disciplines of science as well, depending on the subject. For example, if one is studying adaptations of life in an
aquatic system, concepts and processes studied in the discipline of physics must be considered. The investigator must examine factors related to the hydrology of the aquatic system that impact a vast web of life from tiny diatoms to the largest whale.

*Science for All Americans* (AAAS, 1989) recommended a very broad definition of science literacy that relates to an individual’s values, attitudes and skills. These “scientific habits of mind” (p. 133) include values, “inherent in science, mathematics, and technology; the social value of science and technology; the reinforcement of general social values; and people’s attitudes toward their own ability to understand science and mathematics” (p. 133), and particular skills (i.e., computational skills, quantitative reasoning, manipulative and observation skills, communication skills, and critical-response skills).

**Literature on How Teachers Negotiate Novel Science and Technology into Curriculum**

Over the past 30 years in particular the science education community has substantially expanded knowledge of students’ understanding of science concepts and the nature of science. This has been accompanied by a paradigm shift in thinking about the ways in which learners, including teachers, construct their own scientific knowledge and understanding (Hofstein & Lunetta, 2003). During the 1980s and forward, the centrality of the Piagetian theory found in the empirical literature diminished as attention was increasingly focused on developing a constructivist view of learning (Hofstein & Lunetta, 2003). A constructivist model currently serves as a theoretical organizer for many educators who are interested in studying both teacher and student cognition in science (Lunetta, 1998).
Specifically, researchers such as Millar and Driver (1987), Driver (1995) and van den Berg, Katu, and Lunetta (1994) have focused their research lens on how teachers apply a social constructivist approach to learn and develop strategies used for conducting science in laboratory settings. A common theme found in these research reports is that what teachers do matters. They found that teachers who incorporate hands-on laboratory activities combined with other carefully selected activities such as working with conceptual organizers like analogies and concept maps produce higher levels of student learning. Indeed researchers such as Williams and Hmelo (1998); Tobin (1990); Brown, Collins, and Duguid (1989); Wenger (1998); and Millar and Driver (1987) who conducted studies on how teachers integrate new science and science teaching strategies into their practice reported that when laboratory experiences are integrated with other metacognitive learning experience, learning is improved.

However, according to a meta-analysis of research conducted up until 2003 conducted by Hofstein and Lunetta (2003) although a large percentage of teachers ascribe to a social constructivist approach to teaching and learning, many teachers failed to utilize or manage combination of laboratory experiences and other experiences effectively. Tamir (1989) wrote that many teachers have very limited direct experience as learners to develop the skills necessary to organize meaningful experiences that integrate experiences using laboratory technology and other modes of learning science. Loucks-Horsley and Matsumoto (1999) suggested that this is in part because policy-makers and teacher educators assume that participating in science laboratory work during the period of preparation to become a teacher is sufficient to prepare teachers to know how plan and
organize laboratory lessons in their own classrooms. They pointed out that despite the fact that this assumption appears to be widely held; a growing body of literature on teachers’ conceptual and pedagogical knowledge and teaching practices does not support this assumption (Loucks-Horsley & Matsumoto, 1999).

The power of placing lead teachers in central roles in the development of teaching strategies and curriculum to negotiate the inclusion of novel science and technology into the curriculum is very visible in the work conducted by Krajcik, Blumenfeld, Marx & Soloway (2000) and by Fishman, Soloway, Krajcik, Marx, and Blumenfeld (2001). These studies engaged teachers as learners working with novel science and novel technology to promote inquiry, meaningful practical activities over a long period of time with coaching support. Although these studies make important contributions to the field, unfortunately, at present there are relatively few projects of this kind that provide design-based, long-term support for teachers as they negotiate the inclusion of novel science and technology into the curriculum (Hofstein & Lunetta, 2003).

Scientific inquiry. The report published in 2007 by the National Academies entitled Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future calls for a multi-level response to meet the growing need to improve the levels of scientific literacy in the U.S., beginning with a recommendation to improve science education through implementing educational reforms. A key strategy identified by the National Science Education Standards (NRC, 1996), the Framework for K-12 Science Education (NRC, 2012) and the early drafts of the Next Generation
Standards (2013) cited scientific-inquiry as the key pedagogical approach to reformed science education in this country.

For clarity, I operationalize the term *scientific inquiry* by drawing upon the definition established by the National Science Education Standards (NRC, 1996):

Inquiry is a multifaceted activity that involves 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. Inquiry requires identification of assumptions, use of critical and logical thinking, and consideration of alternative explanations (p. 23).

In contrast to the way excellent science teaching has been defined in the past in terms of using the scientific method of discovery as a standardized, proscribed step-by-step approach to conducting scientific investigations, this National Science Teacher Association (NSTA) policy statement (2010b) on the definition of scientific inquiry supports the idea that there is actually no fixed sequence of steps that should be applied to every scientific investigation. In fact, the nature of science is such that different questions and observations suggest different protocols and procedures. What is central to scientific pursuits is the importance of gathering and analyzing empirical data using appropriate tools and instruments. This process of learning how to frame questions and figure out which tools are appropriate to use to pursue the development of a body of evidence to support a claim or simply describe observations is central to learning science and how contemporary science is done (NRC, 2012). Throughout this process, scientists must bring to the work a healthy dose of skepticism when assessing their own research and that of others and be open to the idea that the evidence they collect may change perceptions
about the world and increase scientific knowledge that is empirically based and logically consistent (NSTA Science Inquiry Policy Paper, 2010a).

**Evolution of the concept of scientific literacy.** The interpretation of scientific literacy articulated in Project 2061 and the NSTA (2010a) Science Inquiry Policy Paper includes ideas from earlier definitions. Shen (1975) argued that scientific literacy consists of three dimensions: “(a) an understanding of the norms and methods of science (i.e., the nature of science); (b) an understanding of key scientific terms and concepts (i.e., science content knowledge); and (c) an awareness and understanding of the impact of science and technology on society” (p. 44). Furthermore, Shen suggested that there are three categories of scientific literacy that relate to those three dimensions, practical, civic and cultural, each of which relate to what the average citizen needs to know and be able to do. Without a basic level of scientific literacy in these three areas, Shen’s supposition is that people are less prepared to meet the daily demands of life such as figuring out a financial budget, planning healthy meals or making well informed choices about which products to purchase and how they participate in the political process (AAAS, 1989; National Science Board, 2002).

The scope of the AAAS (1989) vision of scientific literacy is not limited to traditional key concepts of the scientific disciplines (biology, chemistry, physics, etc.) but also incorporates knowledge from mathematics, technology and the social sciences. According to the AAAS publication entitled *Science for All Americans*, this seminal work identifies science as a complex social activity that is the union of science, mathematics
and technology; it is this complex matrix that makes the scientific mode of knowing so successful,

The focus is consequently on the scientific world view, scientific methods of inquiry, the nature of the scientific enterprise, features of mathematics and mathematical processes, the connection between science and technology, the principles of technology itself, and the connection between technology and society.

(p. 1)

Various aspects and nuances of inquiry are further described in the empirical literature (e.g., Karplus & Butts, 1977; Laugksch, 2000, Llewellyn, 2002, NRC, 2000), but the essential definition of scientific inquiry found in the empirical literature is clear—students critically and systematically engage in examining, interpreting, and analyzing questions regarding the world around them, and then communicate their findings, providing convincing evidence-based arguments for their conclusions.

A central tenet of science holds that scientific theories are never proven but instead theories are supported or falsified. It follows than that a central purpose and value of engaging in scientific inquiry is to apply higher order thinking skills to critically examine theories and knowledge claims, rather than to simply criticize or support ideas about the natural or built world without logically drawing upon evidence to support or refute a belief or understanding. Learning through inquiry supports learning with understanding so that knowledge is applicable and useful (Harlan, 2004).

Critique of scientific inquiry-based instruction as a vehicle for reform. Critics from within the field of education claim that inquiry-based education often relies too much on a Piagetian focus that seeks to help students to resolve their common
misconceptions through the inquiry process without moving beyond that effort to learn new skills and knowledge (Kirschner, Sweller, & Clark, 2006). The NSTA (2010b) policy statement on science inquiry seeks to address this complaint by pointing out that combining Piaget’s ideas about debunking student’s misconceptions along with Vygotsky’s activity theory approach to scaffold learning via the zone of proximal development is a much more progressive approach to teaching science as inquiry. This approach moves students through a series of developmental phases focused on the development of higher order thinking skills used to investigate natural and man-made phenomena rather than simply disproving misconceptions in science through rote memorization of knowledge (Tomlinson, 2003).

Others criticize the pedagogy of scientific inquiry in part because of a failure of some to clearly distinguish the discovery science approach from a guided inquiry or open-ended (Kirschner et al., 2006) mode of inquiry. The discovery science approach is one in which the instructor is all but removed from the process, whereas a guided or open-ended inquiry process is a more rigorous approach to inquiry-based learning characterized by a carefully facilitated process of exploration and sense making (Marshall, Smart, Lotter, & Sirbu, 2011).

In an effort to clearly define what is meant by the modes of scientific inquiry, researchers have sought to describe the hallmarks of inquiry learning, regardless of where the inquiry process is situated on the continuum of discovery science to open-ended inquiry described by Marshall et al. (2011). These hallmarks include either a teacher or student posing guiding questions that are often refined by students (Krajcik, Blumenfeld,
Marx, Bass, Fredricks, & Soloway, 1998; Metz, 2000), engaging students in the process of designing and implementing complex and often open-ended investigations (Chinn & Malhotra, 2002; Edelson, 2001), drawing on a variety of experimental methods (Kuhn, Black, Keselman, & Kaplan, 2000) to collect data and evidence and exploring connections between alternative representations (e.g., molecular, symbolic, and observable) of the phenomena (White & Frederiksen, 1998). From there, students engage in the formulation of explanations (McNeill & Krajcik, 2008; Sandoval & Reiser, 2004) that consider multiple perspectives on a problem and integrate and apply their ideas (Clark & Linn, 2003; Linn & Hsi, 2000).

**Assisting Teachers to Fit Nanoscale Science and Technology Into the Curriculum**

Nanoscale science and technology ranks among the forefront of novel content knowledge and skills teachers must find a way to include in an already packed curriculum (Stevens et al., 2009). Although we do not know exactly what the best combination of resources for teachers may be, research conducted by the NCLT has provided an understanding of how some teachers are currently integrating nanoscale science into classrooms and ideas of what teachers need to learn to improve those current strategies (Bryan et al., 2007).

Prior to the NCLT workshops, Bryan et al. (2007) found that many teachers in their program viewed the inclusion of nanoscale images and models as most suitable for “show-and-tell” during direct instruction rather than hands-on, inquiry-based interaction with the technology. Thus, Daly and Bryan (2007) claimed that without having hands-on experiences themselves, working with nanoscale science and technology teachers have
difficulty figuring out appropriate ways to weave in novel scientific concepts and technology into the curriculum. Even with access to readings, ideas for activities and other resources found on-line and elsewhere, teachers reported difficulty in choosing effective teaching strategies to actively engage all students in learning and to assess student-learning outcomes (Daly & Bryan, 2007).

Two themes emerge in the empirical literature demonstrating how teachers are currently approaching the process of negotiating the inclusion of nanoscale science and technology into the curriculum. Daly and Bryan (2007) found that in the classrooms of the teachers they studied, nanoscale scientific concepts are routinely taught by focusing primarily on the big ideas of size and scale and by having students create and manipulate models. In another study Steven, et al. (2007) found that nanoscale science is often addressed by giving examples of how nanoscience is used to benefit society. In yet another study also conducted by members of the NCLT, researchers noted that many teachers reported they tack on experiences with technology to the end of a unit to reinforce learning only if there is time available to do so (Bryan et al., 2007; Hutchinson, Daly, & Bryan, 2009). In all of these cases, the researchers found that the link between nanoscale structures, their morphology, chemistry, and behavior is often illusive and abstract.

NCLT researchers point out that without a significant impactful experience, scientific concepts may never solidify in a student’s mind in terms of a higher-order level of understanding Stevens, et al. (2007) and Bryan et al. (2007) claimed that teachers struggle with developing highly impactful lessons to do with the nanoscale because they
lack content knowledge and knowledge of subject specific instructional strategies related to nanoscale science and technology and a lack of PCK related to integration of nanoscale technology in the curriculum.

Using a design-based research approach, the NCLT researchers (Magnusson et al., 1999) drew upon their design-based research experiences providing nanoscale related teacher PD to develop four recommendations for enhancing teacher’s PCK:

1. Helping teachers examine their preexisting ideas and beliefs
2. Addressing the relationship between subject matter knowledge and PCK
3. Situating learning experiences for teachers in meaningful contexts
4. Using a model of components of PCK to guide learning-to-teach experiences.

Based upon these recommendations, the NCTL changed their teacher PD workshops to include more explicit information on the power of hands-on, inquiry-based learning for K-12 students and the ability to bring the nanoscale into those students’ realm of consciousness (Bryan et al., 2007). Bryan et al. found that for educators to understand students’ thinking, it is optimal for teachers to participate in an inquiry process in much the same way they ask their students to do. They noted that teachers enrolled in the NCLT teacher PD courses because they wanted to learn how to use nanoscale technology, not because they wanted a course on pedagogy. However, when teachers engaged in the process of doing science themselves, they felt the constraints of time, technical limitations, lack of knowledge, and frustration over misconceptions in science, and other factors that contribute to the student experience. Through a hands-on experience, teachers build upon their knowledge base for how to anticipate student
experiences and design lessons that accommodate for certain patterns of student thinking (Bryan et al., 2007).

For example, while in the role of the learner in a PD course, teachers have the chance to engage in doing scientific inquiry. They reflect on how a probing or guiding question from an instructor or colleague affects their own thinking, learn to anticipate ebbs and flows in the inquiry cycle and consider how alternative conceptions or misconceptions may be challenged and disproved. To unpack this experience, NCLT PD leaders purposely built in opportunities for teachers to engage in reflective discourse within the context of doing the inquiry so that teachers understood in an immediate sense the value of the insights they were gaining through the experience and how to apply these ideas in their own classroom practice (Bryan et al., 2007).

As a result of having hands-on inquiry experiences themselves, teachers involved in the NCLT workshops changed their teaching strategies (Bryan et al., 2007). Instead of merely viewing textbook or on-line images of nanoscale objects, their students used tools in real time to manipulate a remote scanning electron microscope to personally examine a specimen. The students of teachers involved in the NCLT workshops made quantitative measurements of objects that revealed compositional differences in objects at the submicroscopic scale, and they viewed submicroscopic objects in three dimensions by manipulating the position of the sample relative to the electron beam.

Teachers reported that their own experience of using the control center to examine specimens, capture and save digital images, manipulate the computer and insert their images into reports, brochures, oral presentations, and videos better prepared them to
engage their students in authentic scientific inquiry experiences. These authentic experiences provided learners with opportunities to build skills that transcend the nanoscale science unit of instruction (Stevens, 2009). Working with the objects, concepts and technology took conceptual and procedural learning off of the blackboard (or whiteboard) and placed authentic research into the hands of students, making science contemporary, fun, and exciting (Bryan et al., 2007; Stevens, Shinn et al., 2007).

**Effective Teacher Professional Development**

As stated above, teachers need assistance in the form of quality PD to navigate the task of choosing appropriate strategies for integrating novel science and novel technology into the curriculum. Here, I present literature that defines what is meant by the term *effective PD*.

In a meta-analysis of research on teacher PD, Darling-Hammond and McLaughlin (1995) found that PD of high quality focuses on “concrete tasks of teaching, assessment, observation and reflection” (p. 598). Building on this meta-analysis and other reports, the NSDC (2009) developed, “Professional Learning in a Learning Environment: A Status Report on Teacher Development in the U.S. and Abroad” technical report. Conducted by members of the School Design Network at Stanford University, and posted on the NSDC (2012) Learning Forward website, the report lists four prerequisites for effective professional learning:

1. Committed educators must first recognize that without continuous opportunities to deepen and expand their practice in an effort to increase their portfolio of skills and practices used to improve student achievement, teachers’ abilities erode over time.
2. Teachers are more likely to engage in professional learning with receptive hearts and minds within partnerships among professionals who engage with one another to access or construct knowledge, practices, skills, and dispositions. Teachers want PD that is relevant and useful and align with standards.

3. This collaboration between partners requires that educators value multiple experiences and perspectives, actively listen to one another, hold student’s best interests at the center and trust that colleagues share a common goal and vision. Teachers must be honest about their abilities, challenges, practices and results. When trust and accountability for results are valued, professional development strengthens the profession and results for students.

4. Because adult learners’ needs differ, professional development programs must differentiate instruction in terms of the levels of experiences they provide, the pacing of the experience and the degree of support provided to teachers as they negotiate translating new learning into practice. For some, acknowledgement of different needs requires courage, determination and patience to continue learning until the practices are effective and comfortable.

(Learning Forward, p. 3)

Building on the findings in this status report, the NSDC then submitted an amendment proposal to section 9101 (34) of the Elementary and Secondary Education Act as reauthorized by the No Child Left Behind Act of 2011. The proposed amendment defined PD as “a comprehensive, sustained, and intensive approach to improving teachers’ and principals’ effectiveness in raising student achievement” (Learning Forward website, 2011, para. 3). The amendment states that PD fosters collective responsibility for improved student performance and must be comprised of professional learning that is aligned with rigorous state standards and local school improvement goals that inform a clear set of learning goals with measurable outcome targets.

However, effective PD supports teaching that goes far beyond having a well-developed toolkit of activities (Berry & Milroy, 2002; Hoban, 2002). This observation goes to the heart of what an excellent teacher PD program provides (Loughran, Mulhall
& Berry, 2008). An effective PD must shift understanding of teaching to seeing the practice of teaching as problematic and the antithesis of transmissive teaching. An effective PD must build upon teachers’ accumulated wisdom of practice active in their thinking. Moreover, an excellent PD does not simply deliver a set of activities a teacher can pick up and easily use tomorrow in class, although this may be one element of a PD. Instead, a well-conceived PD works with teachers to help them draw upon available knowledge such as ideas about how people learn, the learning environment, the subject specific content and the interaction between these elements to deepen their thinking about how to teach specific topics (Cohen & Ball, 2001).

Excellent PD provides both new content and opportunities for teachers to collaboratively build upon and develop pedagogical reasoning by exploring applications of high-leverage practices that include tested and fresh ways to approach familiar content (Cohen & Ball, 2001). A high-leverage practice is highly impactful on student learning. An example of a high-leverage practice is including activities that provide opportunities for student to test their own ideas and alternative concepts or misconceptions rather than simply telling a student a set of facts without engaging them in problem solving, questioning ideas or learning applications of ideas (Mirel, 2011).

Within PD contexts, the process of thinking in community supports teachers’ abilities to develop logical rationales about how one selects from a choice of strategies to represent knowledge in ways that promote student thinking and learning in complex environments (Mirel, 2011). Dewey (1902) referred to this process as translating discipline-based knowledge into life-terms. Excellent PD helps teachers to develop their
ability to adjust, adapt and make appropriate professional judgments throughout lessons in response to evidence of student learning (Loughran et al., 2006).

Nanoscale science provides an interesting case for content-based teacher PD because it is new content for most, if not all, of the teachers involved in the work of integrating this relatively novel area of science into the curriculum. Nanoscale science can be used as a vehicle to teach familiar topics related to properties of matter such as concepts related to size and scale. Despite the development of knowledge of the nanoscale over the past 20 years, science curriculum typically primarily addresses properties that occur on the macro, micro and to a lesser extent, atomic scales. Thus far, information about nanoscale is, for the most part, overlooked in contemporary science curricula. This omission is significant because matter functions differently on the nanoscale than it does on any other scale. For example, color becomes a size-dependent property; intermolecular forces begin to overcome gravitation forces and magnetic materials behave differently (Winchow, 2010). Therefore omitting information about size-dependent properties of matter could contribute to creating misconceptions in science in the minds of students. To remedy this situation, teachers can learn nanoscale concepts at the same time that they are developing relevant PCK and strengthening their metastrategic thinking in PD settings.

This integration of known and novel information related to properties of matter requires that teachers have the opportunity to learn new content and draw upon their existing content knowledge and PCK to adapt lessons for their classroom in a way that developmentally makes sense to students (Winchow, 2010). Because we live in a society
where rapidly emerging science knowledge and technology is the norm, integrating novel content into the curriculum is becoming an increasingly frequent activity for teachers (Cox & Graham, 2009; Mishra & Koehler, 2006). Therefore, examining the complexities of how teachers learn and build upon what they know to figure out how to logically approach teaching novel ideas using novel technology is an interesting process – an interesting process that requires an examination of literature describing what is known thus far about how teachers draw upon metastrategic thinking and PCK to negotiate emerging challenges in the classroom.

**Metastrategic Knowledge**

As described in Chapter One, metacognition is knowledge about the thinking processes necessary for understanding and learning (Flavell, 1976). The concept of metacognition gained prominence in the 1970s with Flavell who described metacognition as having knowledge, having control over thinking and applying that knowledge (Flavell, 1976; Tei & Stewart, 1985). Because metacognition is crucial to comprehension, it serves as an essential component of learning (Flavell, 1976).

Metastrategic knowledge, one of two primary constructs that frame this study, is defined as a subcomponent of metacognition; metastrategic knowledge is a person’s knowledge specifically related to higher-order thinking strategies (Ben-David & Zohar 2009). From my perspective, knowledge is something that someone possesses, whereas thinking is something that a person does. Thus, examples of metastrategic thinking that draw upon higher order strategies are the ability to evaluate and classify, integrate knowledge from various sources, plan experiments and draw conclusions (Ben-David &
Zohar, 2009). Teachers employ metastrategic thinking to learn multiple teaching strategies, such as when to apply specific strategies, when to implement specific strategies and under what conditions to achieve a teaching goal (Wilson & Bai, 2010).

Despite increasingly widespread recognition of the role of metacognitive thinking in student success (Sternberg, 1998), limited research has been conducted to examine the role of teacher’s metastrategic knowledge and the relationship between how teachers draw upon this form of thinking, their content knowledge, PCK and knowledge of students to inform their decision making process throughout the cycle of a lesson (Wilson & Bai, 2010; Zohar, 1999). Literacy research in the area of metacognition clearly delineates that students need models of strategies in action, guided practice as they experiment with and apply strategies, and independent practice with using various strategies for negotiating meaning (Griffith & Ruan, 2005). Understanding how to guide students’ thinking is part of a teacher’s professional and experiential repertoire commonly referred to a PCK.

The Relationship Between metastrategic thinking and PCK. I submit that teachers’ metastrategic thinking and PCK inform one another in a two-way relationship. I am inspired by the work of Ben-David and Zohar (2009) to conceptualize the framework of metastrategic knowledge in active terms; thus, I used the term and construct metastrategic thinking to frame this research rather than metastrategic knowledge. I posit that teachers employ metastrategic thinking to interpret learning and teaching situations so that they can develop a rationale for how to respond to learners’ needs to meet a specific teaching goal involving students’ higher order thinking. This rationale is then
applied as teachers draw upon their PCK to select strategies to teach specific topics as is appropriate given particular conditions (i.e., awareness of the content, curriculum, common misconceptions or other barriers to learning specific topics and knowledge of the needs of individual and group of students). Throughout the implementation of lessons, teachers draw upon metastrategic thinking to adjust those lessons to better suit the needs of learners by drawing on the repertoire of their PCK to know how, when and why to adjust activities to meet specific teaching goals (Baily & Nunan, 1996).

In other words, metastrategic thinking is not simply a skill that teachers learn once; rather, teachers evolve in their conception of what it means to think and learn (Harpaz, 2007) as they develop their PCK, especially about how to encourage higher order thinking in their students. This process of teacher thinking is not a linear one, but instead it is a cyclical process constantly informed by feedback from students and teachers’ reflective practices (Baily & Nunan, 1996). As teachers develop a wider array of instructional moves to apply in various situations (i.e., PCK), their abilities to apply metastrategic knowledge and PCK expand. Next, I provide a review of literature that describes the construct of PCK and the definition that I chose to inform this study.

**Pedagogical Content Knowledge (PCK)**

The construct of PCK is a second major conceptual framework that guides this proposed dissertation study. In the area of science education, scholars such as Anderson and Mitchner (1994), Hewson and Hewson (1988), Cochran, King, and DeRuiter (1993), and professional organizations such as the National Council for the Accreditation of
Teacher Education (NCATE, 1997) and the National Science Teachers Association (NSTA, 1999) emphasize the value of PCK for teacher PD.

The concept of PCK was first proposed by Shulman (1986) and his colleagues as a broad-perspective model for understanding teacher’s knowledge and teaching.

Shulman (1986) described PCK as, “the most useful forms of representations of ideas, the most powerful analogies, illustrations, examples, explanations, and demonstrations—in a word, the ways of representing and formulating the subject that makes it comprehensible for others” (pp. 9-10). In Knowledge Growth in Teaching (1988) Shulman and Grossman described PCK as knowledge formed through the synthesis of three knowledge bases: subject matter knowledge, pedagogical knowledge, and knowledge of the curriculum. Importantly, Shulman and Grossman (1988) stated that PCK includes understanding what topics may be difficult or easy for learners to understand, as well as the barriers or limitations to individual’s learning including commonly held misconceptions. Shulman (1987) claimed that PCK is the best knowledge base for teaching because the key to teaching is in the capacity of a teacher to transform his or her knowledge base of content “into forms that are powerful and yet adaptive to the variations in ability and background presented by the students” (p. 15).

In the field of science education research, Cochran, King and DeRuiter (1991) make the point that teachers differ from biologists, education researchers and writers not necessarily in their quality and quantity of subject matter knowledge, but in their awareness of how subject matter knowledge is organized and used for teaching. Based on a series of empirical studies conducted over a number of years, Loughran et al. (2006)
claimed that teachers’ awareness of how to organize information so as to reach students—that is, PCK—is particularly rich and fertile ground for exploring and highlighting exemplary thinking about science teaching in a way that can be communicated to a wider audience.

Since Shulman (1986, 1987 and his colleagues (Magnusson et al., 1999; Shulman & Grossman, 1988) introduced the construct of PCK in the late 1980s, some scholars have expanded upon Shulman’s earlier ideas and others have somewhat redefined the construct. For example, within the framework of science education, Magnusson et al. (1999) defined PCK as consisting of five components: (a) orientations toward science teaching (teacher goals and general approaches to science teaching); (b) knowledge of science curriculum; (c) knowledge of assessment for science; (d) knowledge of science instructional strategies; (e) knowledge of student science understanding.

Each of the definitions I read share the common ideas that PCK is a framework useful for examining teachers’ professional knowledge of science content and curriculum, knowledge of how students learn and understand science, knowledge of assessment and knowledge of instructional strategies. There are, however, important differences in terms of the way in which various researchers have applied the lens of PCK to research. For example, unlike Shulman’s presentation of PCK, Veal and MaKinster’s (2010) description of PCK also included external social forces that drive teachers’ choices of how to teach—for example, social forces such as pressuring educators to teach to the statewide test, teaching the way one was taught, implementing scripted
curriculum with fidelity and participating in reform initiatives that promote specific approaches to elements such as planning and assessing student learning all impact teachers’ choices of how and what to teach. Although I agree that external social forces certainly impact a teacher’s decisions about how and even what to teach, for the purposes of this dissertation, I restrict my definition of PCK to the way Shulman originally described PCK and how Magnuson, Krajcik and Borko (1999) have gone on to define levels of PCK, which I describe later.

**Technology PCK.** Another important development in the field of research related to PCK is the concept of technical pedagogical content knowledge (TPACK), introduced by Mishra and Koehler (2006). The TPACK (also known as TPCK) conceptual framework builds upon Shulman’s (1987) formulation of PCK and extends it to include the phenomenon of teacher’s integration of technology into teaching and learning (Mishra & Koehler, 2006). Mishra and Koehler argued that TPACK is a situated form of knowledge that involves the complex role of, and interplay among content, pedagogy, and technology. The primary focus of this perspective is not necessarily on technology itself, but on how teachers use technology to support contextually bound, specific teaching goals (Mishra & Koehler, 2006).

In an attempt to clarify the major ideas related to TPACK, Cox and Graham (2009) conducted a conceptual analysis of interviews with educational researchers that resulted in the following definition of each construct within the TPACK framework:

TPACK refers to a teacher’s knowledge of how to coordinate the use of subject-specific activities or topic-specific activities with topic-specific representations using emerging technologies to facilitate student learning. As the technologies
used in those activities and representations become ubiquitous, TPACK transforms into PCK (p. 64).

Although in the initial work to establish a conceptually based theoretical framework of PCK Shulman (1986, 1987) did not discuss technology and its relationship to pedagogy and content, technology has since come to the foreground of educational discourse due to the availability of a range of new, primarily digital technologies and the requirements for teachers to build knowledge and skills for how to apply them to teaching (Mishra & Koehler, 2006). Cox and Graham reported that their research findings support the claim that given the rapid expansion of technology on a fairly constant basis, there will be a need for the TPACK framework in the field of educational research as long as teachers will be required to continue to build upon their repertoire of tools to negotiate the inclusion of new technology into their practice.

Based upon this need, scholars have sought to establish a theoretical framework of TPACK. Interestingly, Mishra and Koehler (2006) pointed out that the current discussion about the role of technology in teaching seems to share many of the same problems that Shulman identified in the 1980s. For example, prior to Shulman’s seminal work on PCK, knowledge of content and knowledge of pedagogy had become for many to be considered separate domains of knowledge (Mishra & Koehler, 2006). Similarly, knowledge of technology is often treated as separate from knowledge of content and knowledge of pedagogy (Ball, 1990; 1996). Just as Shulman attempted to address this artificial and potentially damaging divide between pedagogy and content, scholars working to develop the construct of TPACK are endeavoring to investigate and describe
how, when and why teachers’ knowledge of pedagogy, content and technology overlap in a complex and nuanced relationship (Cox & Graham, 2009).

Although the TPACK framework is important and certainly relates to the present study, my research questions encompass a broader inquiry regarding both how teachers negotiate the inclusion of novel science content and technology into the curriculum; therefore, I chose to maintain a central focus on the broader frameworks of metastrategic knowledge as described by Ben-David and Zohar (2009) and PCK as described by Shulman (1986;1987) and elaborated upon by Magnusson et al. (1999), rather than narrowing the focus to TPCK. The following section provides further clarification of the description of PCK that I applied in this study.

Levels of PCK. As mentioned above, Magnusson et al. (1999) describe a taxonomy of levels of PCK: subject-specific, domain specific and topic-specific PCK. Figure 2 depicts these three levels of PCK on the next page:
Magnusson et al. (1999) argued that the process, purpose and content or subject-matter— that is, subject-specific PCK—would not be the same in a science classroom as it would be in a non-science classroom. For example, in science the student engages in a similar process of learning facts and applying critical analysis of ideas as a student would do in any process of learning. However, the nature of science involves the application of protocols and procedures for conducting scientific inquiry including making predictions, forming a hypothesis, choosing instruments to explore and test ideas using the tools of science, using logical thinking to interpret data, building a body of evidence to support a
claim or describe an observation and proposing alternative explanations for observed phenomena (NRC, 1996).

Domain-specific PCK is more distinctive than subject-specific PCK because it focuses on one or more specific subject-matters within a particular discipline such as chemistry or biology (Magnusson et al., 1999). For example, the subject of biological adaptations of organisms is most often described in biology courses than in other disciplines of science.

Topic-specific PCK is the most discrete level of PCK in the taxonomy of PCK as described by Magnusson et al. (1999). Each discipline of science has its own sets of concepts, terms, procedures and protocols. For example, thermodynamics is a topic common to both physics and chemistry; yet, the terms used to describe phenomena such as heat and temperature differ. A chemist refers to kinetic molecular theory to describe temperature and a physicist describes temperature as the measure of heat loss or gained in a system. And because of the different approach to understanding natural phenomena, the lab activities differ considerably as well. For instance, you would almost never find a physics teacher burning a peanut in a lab to demonstrate kinetic and potential energy whereas nearly every chemistry teacher in the U.S. is bound to burn a peanut or two every year to describe endothermic and exothermic reactions because this lab activity fits well within the topic-specific and domain-specific PCK of a chemistry teacher.

Individual teachers develop their own PCK over time, with idiosyncrasies influenced by rich conceptual understanding of content, developing, using and adapting various teaching procedures and strategies over time (Loughran et al., 2006). It is this
amalgam of knowledge derived from experience of experimenting with various teaching strategies to teach particular topics, curriculum, content standards and the content itself that contributes to the development of PCK, which teachers then draw upon to figure out how to approach integrating novel content and technology into the curriculum. 

Theoretically, a teacher who has mastery of topic-specific PCK could have a solid repertoire of skills and abilities at all three levels. Conversely, the lack topic-specific content knowledge can also be a significant barrier to drawing upon experience to improve teaching (Darling-Hammond & Baratz-Snowden, 2007).

For example, a teacher in Project NANO has been teaching a forensics science unit in her middle-level science classroom near the beginning of each academic year for over 10 years. She said that the forensics unit is a fun, engaging vehicle for teaching scientific protocol and procedures with her seventh grade students. However, she realized that after 10 years of teaching the unit of instruction much the same way each time, the science and technology used in forensics science has advanced considerably. She knew that it was time to update the unit, but she lacked topic-specific science content and technical knowledge that would invigorate her own planning and the minds of her students. Without new content knowledge, she lacked the subject-specific and topic-specific PCK to envision new ways to approach teaching lab protocols used in forensic science. Nor was she able to visualize new domain-specific forensic science lab activities in ways that deepened student thinking. After she learned about how a scanning electron microscope is used by professional forensic scientists to investigate properties of matter at the nanoscale, her level of PCK expanded which helped her to figure out how to raise
the level of student-centered inquiry to include higher order thinking skills using the an
SEM and high powered light microscope in addition to the other scientific methods she
had traditionally asked students to do to investigate a crime scene.

**PCK as a Lens to Illustrate Portraits of Practice.** Loughran et al. (2006) claimed that the important and unique professional knowledge of teachers, particularly PCK, should be recognized, developed and valued in education. By and large, much of the educational research conducted on PCK has focused on comparing and contrasting the practices of individual teachers (e.g., Magnusson & Krajcik, 1993, heat energy and temperature) and of groups of teachers (e.g., Clermont, Borko & Krajcik, 1994, density and air pressure). Very little research has been conducted that contributes portrayals of PCK related to teaching specific topics (Loughran et al., 2006).

Complex ideas associated with exemplary practices tend to be better understood by the producers and consumers of illustrations of teaching when framed around specific scientific topics (Loughran et al., 2006). One reason is that by focusing on strategies to teach specific topics, shared language is established. A shared language of practice provides access to understanding portrayals of practice in such a way that underlying metastrategic thinking and PCK about the choice of strategies for how to frame and teach a specific topic is revealed (Zohar 2006). The ability to communicate metastrategic thinking in relation to how to teach specific topics in science provides the means to move beyond the idea that good teaching is simply an accrual of activities (Zohar 2006).

Loughran et al.’s (2006) group pointed to the importance of using the PCK framework in research to develop resources for specialists that characterize topic-specific
language teachers draw upon to describe pedagogical strategies used to engage students in thinking about ways to approach complex ill-defined and authentic tasks. As mentioned above, it is not sufficient for PD to merely serve up a toolkit of information or activities teachers may draw upon to develop and teach a unit integrating nanoscale concepts. If PD is to be impactful on teaching practice, science education opportunities provided to teachers must take into consideration the importance of language to establish shared understanding (Loughran et al., 2006).

Beyond establishing a shared language to facilitate understanding of metastrategic thinking and PCK that underlies how teachers choose to frame and implement lessons on very specific topics, PD providers must also consider fundamental concepts of adult learning theory if they are to successfully change teachers’ practices. Here I elaborate on literature that describes some key aspects of adult learning theory relevant to this study.

**Learning Progressions**

The concept of learning progressions serves as a major guiding construct for thinking about student learning in the Next Generation Science Standards (Achieve, 2013) and the Framework for K-12 Science Education (NRC, 2012). The concept of learning progressions is also recently gaining attention within the science education community as a useful construct to apply to teacher learning, especially in relation to teachers’ development of their PCK over time (Schneider & Plasman, 2011). According to Schneider and Plasman (2011), “The characteristics of learning progressions are that progress is: continuous and coherent, an incremental sequence from novice to expert performance, and mediated by instruction” (p. 532).
Ball and Cohen (1999) suggested that in order to improve teacher PD, providers should think about teachers becoming successively more sophisticated in their thinking as they spend time in the classroom and are supported by opportunities for learning and PD. Although they did not use the actual term, researchers such as Berliner (1994) and Ball and Cohen (1999) note that the notion of learning progressions for teachers is consistent with descriptions of the stages of teacher development and what expert teachers should know and be able to do at each of those stages.

Bransford (2001) described teachers’ development in terms of *adaptive expertise*. He described adaptive experts as those who relish challenges and are willing to develop new habits of mind, attitudes, and ways of thinking to stretch their knowledge and abilities. He went on to say that adaptive experts are able to tolerate ambiguity and reassess previously held assumptions as they engage in learning new skills and knowledge. Schneider and Plasman (2011) wrote that juxtaposed to adaptive expertise is *routine expertise*, a state-of-mind concerned with refining and perfecting existing structures to maintain consistency in teaching.

Schneider and Plasman (2011) claimed that, “adaptive experts are much more likely to evolve their core competencies and continually expand the breadth and depth of the expertise as the need arises or as their interest demands” (p. 532). They stated that doing so often requires teachers to function as “intelligent novices” (p. 532) who experience authentic learning opportunities in much the way their students are likely to experience learning. In some cases, they may initially struggle in order to learn new things (Bransford et al., 2005); thus, the opportunity to reflect on limitations and even
barriers to learning and solutions for these barriers is a potentially powerful socially constructible experience for teachers to apply to clarify and build their PCK.

Although adaptive expertise is a relatively recent refinement of the idea of expertise, thinking about trajectories can be guided by what is known about the development of expertise, describing trajectories from novices to adaptive experts. PCK may be thought of as a heuristic for teacher knowledge that can be helpful in untangling the complexities of what teachers know about teaching and how it changes over time.

Researchers such as Carter (1990) and Munby, Russell, and Martin (2001) have claimed that it is necessary to consider teachers’ PCK ideas directly rather than examine subject matter, pedagogical, and context knowledge to infer PCK. Moreover, PCK, in contrast to practical knowledge (knowledge of classrooms and the complexities of teaching), is more formal and built on the collective wisdom of the profession (Carter, 1990).

Currently, there is a considerable body of literature on learning progressions for pre-service and novice teachers (e.g., Schneider & Plasman, 2011); however, there are very few studies that examine teachers’ career-long learning progressions. The career-long research that does exist provides descriptions of teachers’ skills based on comparisons of novice or inexperienced teachers with expert teachers with at least five years of experience (Schneider & Plasman, 2011). Researchers Shavelson (2009) and Heritage (2008) both promoted the idea that the learning progressions construct is most useful to understanding how teachers learn if the lens is applied over a long period of time, rather than during only one short phase of an educator’s career.
Although recent research on student learning progressions aligns with state and federal science content standards and learning targets, Shavelson (2009) cautioned against framing research on teachers’ learning progressions in exactly the same manner as that of students. Both Heritage (2008) and Shavelson argued that rather than thinking about teachers’ learning as a series of discrete events, it is more helpful to think of their learning progressions as a trajectory of development. Both researchers claimed that it is less than helpful to think of the construct of learning progressions as metrics used to measure teachers' learning specific content knowledge as end points. Instead, Shavelson and Heritage both emphasized applying the concept of learning progressions to interpret the development of teachers' expert knowledge that involves increasingly complex thinking over time in response to careful reflection.

Although the focus of this dissertation research was not on describing teachers’ learning progressions over long periods of time, it does contribute to the development of baseline knowledge about teachers’ knowledge specifically related to the inclusion of nanoscale science and technology into the curriculum and provides a model for how to elicit teacher thinking to describe development of their PCK. This dissertation describes various entry points of a small number of teachers involved in Project NANO who each approached the challenge of integrating novel science content and technology into the curriculum from a different entry points depending on their metastrategic thinking and PCK they brought to the situation.
**Adult Learning Theory**

In the 1970s adult learning theory emerged as an approach to distinguishing adult learning from that of children in a formal educational system, with significant volumes by Knowles (1973) entitled *The Adult Learner: A Neglected Species*, later followed by a series of editions leading to the sixth edition entitled *The Adult Learner, Sixth Edition: The Definitive Classic in Adult Education and Human Resource Development* (Knowles, Holton, & Swanson, 2005). In this edition, Knowles, Holton and Swanson described learning as a recursive process that takes places in stages. The growth of knowledge and skills involves a process of revision and construction of cognitive structures, abilities and processes (Knowles, et al, 2005; Piaget, 1964; Vygotsky, 1986). The nature of adult learning is different than that of development in earlier stages of life. Whereas the objectives of a young learner are primarily focused on the acquisition of skills, an adult learner is more concerned with application of skills (Knowles et al., 2005). Knowles et al. (2005) identified the following key assumptions about adult learners:

1. Adults need to know the relevance of something before they begin to learn.
2. Adults are capable of self-direction.
3. Adults have a wealth of experience to draw on.
4. Adults have a readiness to learn what they need to perform effectively.
5. Adults need to be orientated to learning that has real-life application.
6. Adults respond best to internal motivation.

(Knowles, et al., p. 5)
For example, in PD teachers must be engaged by understanding how learning new material will be beneficial to their practice of teaching. Adult learning theory indicates that for information to be credible and useful to teachers, PD must fit with what adults already know. Although children learn most often by building new assemblies of knowledge and skills, adults spend more time making new arrangements of pre-existing knowledge to make room for new information rather than forming brand new sequences of knowledge.

One of the ways such understanding is accomplished in a PD situation is that instructors may structure lessons to draw upon evidence-based teaching principles, which are explicitly referred to and modeled throughout the PD. For example, assisting teachers at a microscope, a PD instructor may explicitly describe the language and actions used to model procedures for how to operate the instrument and also pause to share with teachers the underlying theory that motivates the choice of specific words or actions. However, PD practices such as modeling and explicit explanations are not desirable because teachers are eager to conform to what is taught in the PD, but because evidence must be provided to assist adults to recognize how new information fits with an existing body of knowledge to motivate change to practice (Knowles, Hilton and Swanson, 1998; von Glasersfeld, 1989a).

Researchers Tusting and Barton (2003) pointed out that learning for adults is always related to their real lives, their actual problems and issues, and that those who provide adult education therefore need to try to understand and make practical links to their lived experience. Tusting and Barton summarized:
Most of the models of adult learning developed from within adult education move beyond examinations of learning as a decontextualized process to address questions relating to the meanings of, and motivations for, learning in people’s lives. This may be in terms of self-direction, reflection, autonomy, problem-solving or transformation and recalls, from a different perspective, the intrinsically socially-situated nature of learning that emerged from the review of the psychological literature (p. 32).

This consideration of the distinctive characteristics of adult learning theory is important here because this study is focused on the metastrategic process of adult teachers involved in Project NANO and how they draw upon what they learn through the workshop, coaching and experience of teaching and reflecting upon the units they designed in the summer workshop to build upon their existing content knowledge and PCK. This statement is not to imply that student thinking is unimportant. However, in Chapter One I have firmly established the boundaries of this study to that of the teachers’ metastrategic thinking, PCK and their learning process and only consider student thinking as it informs the teachers’ thinking.

Grace (1996) criticized the theory of andragogy or adult learning theory for focusing solely on the individual and not operating from a critical social agenda or debating the relationship of adult education to the greater society in which adults operate. More recent models of adult learning theory are situated within learning theories of social constructivism, situated cognition, as well as brain science (e.g., Brookfield, 1995). These theories focus on the interaction between people, between people and content, and how these interactions facilitate and reinforce the learning process.

Social Constructivism. Another key construct that is central to Project NANO is that of social constructivism. In Chapter One I discussed ideas related to social
constructivism found in theoretical literature. Here, I cite information from the empirical literature to describe social constructivism.

According to von Glasersfeld (1989b) “the first principle of constructivism [is that] knowledge is not passively received but actively built up by cognizing subject(s)” (p. 162). Constructivism puts the focus on the mind of the learner and on the cognitive processes of the student over time. Social constructivism emphasizes the influence of culture, context, and social interaction on the learning process (Derry, 1999; McMahon, 1997). This perspective is closely associated with the social cognitive theories of Vygotsky (1934), Bruner (1973), and Bandura (1977).

There are several versions of the constructivist learning perspective but all are founded on a building metaphor (Ernest, 1993). Kieran and Pirie (1991) described this metaphor in terms of building up a structure using preexisting knowledge and skills that may be shaped for a specific task. Kieran and Pirie see constructivism as a recursive process wherein “the building blocks of understanding are themselves the product of previous acts of construction” (p. 78).

Furthermore, social constructivist learning theory emphasizes the “essential and constitutive nature of language and social interaction” (von Glasersfeld, 1989b, p. 162). For instance, the concept of social constructivism is prevalent in science education literature and, in particular, is often found in research related to laboratory experiences and other situations where students collaboratively conduct scientific inquiry (e.g., Driver, Asoko, Leach, Mortimer, & Scott, 1994). Social constructivist theory is based on particular assumptions about reality, knowledge and learning—for one, that reality is
constructed through human activity (Kukla, 1994) and for another, that knowledge is also a human product that is socially and culturally constructed (Ernest, 1999; Prawat & Floden, 1994). Finally, although knowledge is ultimately possessed by the individual (Sfard, 1998), learning is a social process that does not take place only in an individual, nor is it a passive development of behaviors shaped by external forces (McMahon, 1997). Rather, meaningful learning occurs when individuals are engaged in social activities (Rogoff, 1990; Vygotsky, 1987). Social groups negotiate and assign meaning to phenomena through the process of dialogue, which enables the development of common understanding of what counts as evidence of knowledge and skills (Solomon, 1987).

**Situated Learning.** Project NANO takes place within a situated learning environment of teachers operating within a community of practice. The program is designed in this way based on Vygotsky’s (1978) idea that it is through the process of learning within a social context that the individual may construct understanding of a phenomenon and develop the capacity to extrapolate knowledge and apply this understanding to another situation without the assistance of another person. Here I present empirical literature related to the theory of situated learning.

In 1988, Collins wrote that situated learning is defined as the notion of learning skills and knowledge in contexts that reflect the way they will be used in “real life” (p. 299). Schell and Black (1997) suggested that situated learning theory encourages educators to immerse learners in an environment that approximates as closely as possible contexts in which their new ideas and behaviors will be applied. Further, Lave and Wenger (1998) described learning as an integral part of generative social practice in the
lived world. Lave and Wenger’s description relates very closely to core beliefs that inform the design of Project NANO and, therefore, bear some analysis.

The term *generative* implies that learning is an act of creation or co-construction; *social* suggests that at least some aspect of the learning occurs in collaboration with others; and *lived-in world* implies real-world practices and situations that make learning more contextually relevant, useful and transferable. For example, a familiar social and environmental context for secondary level science teachers is working with laboratory partners in a school-based classroom laboratory rather than in a university or college-based laboratory setting to conduct a scientific inquiry. Although the content and technology may be new to the teachers, the experience of working in a familiar environment in a typical configuration of people using the same types of resources that their own classroom is likely to have may contribute to the teacher participants’ abilities to visualize how to teach new content in their own classroom. This comfortable and familiar context may help adult learners draw on and build upon their abilities to assign meaning to a PD experience (Tobin, 1990). The ability to assign meaning to a lived experience is a critical step in the learning process as teachers navigate how to fit novel content within their existing corpus of content knowledge and PCK.

In situated cognition environments, facilitation is less directive, more continuous and highly interactive (Schell & Black, 1997). The role of the instructor moves from a knowledge transmitter to the role of coach or facilitator of student learning who assists with the learners’ process of approaching new ideas, negotiating meaning, internalizing information, and developing and using self-monitoring and self-correcting strategies

The concept of dynamic communities of practice (Lave & Wenger, 1991) is a critical element of situated learning. People operating within a community of practice may switch roles throughout the experience of working together depending upon the needs of the individual or group at a given moment. For example, the instructor may switch to the role of the learner and the teacher participant to that of a coach when problem solving a classroom management issue related to how to ensure that all students in a class are constantly engaged during a science laboratory activity.

The role of the content may also shift within a community of practice because knowledge itself is a tool that is only truly useful if one knows how to use it (Lave and Wenger, 1991). To internalize and know how to apply content, it is necessary to consider and discuss similarities and differences among settings to be able to discriminate how best to frame topics (Brown, Collins, & Duguid, 1989; Greeno, 1998; Schell & Black, 1997).

For example, a middle-level teacher working with a high percentage of talented and gifted English language learners (ELL) may conceive of working with students on a laboratory activity very differently than a teacher who works primarily with low-performing students, most of whom are native English speakers. Although the same scientific content may be addressed in the laboratory activity for both groups of students, the teacher may decide to emphasize different supporting learning targets for each group.
The lesson designed for the talented and gifted class that includes a large number of English language learners may be a more open-ended scientific inquiry experience and include a greater emphasis on language acquisition; the lessons designed for a low-performing class may include more structured laboratory experiences that emphasize learning self-monitoring and self-correcting skills in an explicit manner. By working together in a community of practice or team to problem solve strategies for how to adapt lessons to meet the needs of each group of students that teachers are likely to encounter, educators are more able to design authentic, problem-rich student-centered instruction that accommodates diversity and builds upon the strengths of what the students know and can do (Collins, 1988; Lave, 1988; Lave and Wenger, 1991).

Thus far, I have described the role of the context and Project NANO activities in relationship to situated learning theory. A third important topic I address is the role of the scanning electron microscope itself and the relationship of this tool to situated learning theory. Harris, Mishra, and Koehler (2009) pointed out that teacher professional development related to the integration of technology into the classroom typically demonstrate implicit assumptions that the kinds of professional knowledge required of teachers for technology integration are the same, irrespective of whether one is teaching middle-level science, high school biology, chemistry or even a discipline outside of the sciences. The researchers claimed that this approach ignores the variation inherent in different forms of disciplinary knowledge and inquiry as well as the varied pedagogical strategies that are most appropriate for teaching specific content within each domain of science (Harris, Mishra, & Koehler, 2009). Different disciplines have differing
organizational frameworks, established practices, methods of describing evidence and approaches for developing knowledge claims. In the case of the SEM and a research grade high powered optical microscope, the integration of these technologies into the curriculum has deep implications for the nature of content-learning, a fact that teachers’ must negotiate if they are to successfully conceptualize how the pedagogical affordances and constraints of the tools as they relate disciplinarily and developmentally to appropriate pedagogical designs and strategies. Developing metastrategic thinking and PCK requires building an understanding of the potential benefits and limitations of these particular technologies as they can be applied within particular types of learning activities, as well as the educational contexts within which these technologically supported activities function best (Bryan et al., 2009).

Recall that the Project NANO summer workshop is designed to encourage groups of teachers to team up and learn the functions of the SEM and how to use the controls to adjust the instrument. Teachers were encouraged to team up by discipline and/or grade clusters—that is, either middle-level teachers working in laboratory groups or groups of teachers all working to investigate a life sciences related inquiry. The pedagogical intention was to foster the development of social dynamics to provide mutual support. This social dynamic impacted teachers’ PCK related to how to best facilitate secondary level students using the microscopes.

**Applying Social Constructivist and Situated Learning lenses to examine PCK.** Social constructivist and situated learning theories are appropriate lenses to apply to study secondary level teachers’ PCK within the context of the Project NANO PD
experience. Social constructivism and situated learning theories underlie both the Project NANO PD and this research study. It is important to note that each of these theories is based on ideas that inform one another and yet are distinctly separate theories. Social constructivism includes a social component to knowledge building (von Glaserfeld, 1992) whereas situated learning additionally allows the social constructivist to ground knowledge in the context of a given situation (Brown, Collins, & Duguid, 1989).

Congruence between the theories that inform the design of Project NANO and the theories that informs this dissertation study was important because this design-based research examined how teachers operated within a particular social situation to draw upon their PCK to acquire and fit new knowledge and technology into the curriculum. As is the case with Bryan et al.’s (2007) nanoscale science and technology workshops, the domain-specific and topic-specific units that the teachers produced, taught and reflected on were based in social constructivist pedagogy. Therefore, it is important to acknowledge the ideas that frame this perspective about teaching and learning and apply a consistent analytical lens to examine what teachers communicate about why and how they designed their Project NANO unit the way they did and how their ideas evolved throughout the implementation of the unit.

Social constructivism explicitly provides opportunities for teachers to examine their preexisting ideas and beliefs about teaching and learning related to very specific topics (Magnusson et al., 1999; Loughran et al., 2006). Social cognition takes place as learners grapple with powerful referents to specific applications of teaching strategies related to how to teach particular concepts or natural processes using a scientific
approach to knowing (Bertram & Loughran, 2012; Magnusson et al., 1999). This process of actively experiencing the scientific process of discovery both as a learner and as educator working with others supports each individual’s ability to fit novel information within existing mental constructs (Bertram & Loughran, 2012; Magnusson et al., 1999). This step in the learning process is essential to a teacher’s ability to create developmentally appropriate units of instructions that fit coherently within the larger learning cycle of the course he or she teaches.

**Summary**

This study is based upon literature from five major bodies of scholarship: PCK, metastrategic knowledge, learning progressions, adult learning theory and teacher PD as depicted in Figure 3.

*Figure 3. Important constructs for this study.*
Here, the construct PCK refers to Shulman’s (1986, 1987) and Magnusson et al.’s (1999) definitions of PCK. That is, PCK is comprised of multiple forms of knowledge about teaching and learning: knowledge of content, curriculum, student thinking, assessment of student thinking and instructional strategies. Metastrategic thinking is inspired by Ben-David and Zohar’s (2009) description of metastrategic knowledge. Here, metastrategic thinking is defined as the cognitive process of developing a rationale for how to structure learning so as to best support the development of students’ higher order thinking skills, scientific skills and content knowledge. The theory of learning progressions relates closely to the goals of teacher PD; with education and support teachers successively gain increasingly sophisticated PCK used to improve facilitation of quality learning experiences for all students. Quality teacher PD aligns with the Learning Forward national standards that state that teachers’ learn best with highly contextualized, practical learning opportunities that are based on adult learning theory that states that practice is positively impacted when there is a compelling reason and clear application of the content and skills taught and learned in the PD.

Each of these key, inter-related constructs refers to ideas central to the overall guiding framework which shape the Project NANO PD model. For example, Project NANO involves groups of novice to veteran teachers in authentic inquiry experiences intended to support the development of learning progressions for all involved. The design of the learning opportunities for teachers provided through Project NANO draw upon adult learning theory in that the teachers’ own inquiry experiences are meant to result in the application of ideas in the form of a unit of instruction. Teachers then receive on-
going coaching support to encourage that the community of practice continues to share and develop metastrategic thinking that contribute to the further development of each participants’ PCK. In Chapter Three, I describe the methods used in this study to elicit and capture 23 secondary level teachers’ thinking throughout this cycle of learning.
CHAPTER THREE
RESEARCH METHODS

Introduction

This dissertation study was designed to investigate 23 secondary level teachers’ metastrategic thinking and PCK, which was used to navigate the inclusion of nanoscale science and technology into the secondary science curriculum. Chapter Three begins with the research question and sub-questions that framed this dissertation study. I then describe the research paradigm and the learning theories that guided this study. Next, I provide contextual information about Project NANO and my position within the Project NANO team. What follows is a description of the research design and methods, including a description of the unit of analysis, rationale for the choice of research strategies and how each methodology informed the research questions. Next, I provide some background information about my experiences as a provider of science education PD for teachers and describe how these experiences, along with scholarly studies, informed my research question and the choices that I made to define the parameters and methodology of the study. The chapter concludes with a timeline for the study, a discussion related to the limitations of the study and research integrity and finally, a brief description of how this study fits within the broader context of educational research.
The Research Question

The research question that framed this study was: *How do teacher participants in the 2012 Project Nanoscience and Nanotechnology Outreach (NANO) program negotiate the inclusion of novel science and novel technology into the science curriculum?*

There were three sub-questions:

1. Do teachers demonstrate scientific content knowledge gains in response to the 2012 Project NANO summer workshop?

2. Of the nine “big ideas” in nanoscale science and technology, which are the big ideas that teachers choose to teach in their Project NANO unit and why?

3. How, if at all, do teachers metastrategic thinking and PCK change between the beginning of the summer workshop and the reflection period following the implementation of the Project NANO unit?

The relationship between the research questions and sub-questions as they relate to PCK. Participation in Project NANO requires that teachers learn new content and technology and use metastrategic thinking to use and build upon their PCK to negotiate how best to fit nanoscale science related topics and two high powered microscopes into the curriculum. Depending on the discipline of science they teach, their depth and breadth of content knowledge and familiarity with the science content and technology in question, teachers began the process of negotiating the inclusion of novel science and technology into the curriculum from different entry points. Entry points shaped teachers’ metastrategic thinking and the choices they made for how to frame and teach their units. The three sub-questions afforded the opportunity to develop a more complex description of teachers’ metastrategic thinking and PCK, as well as changes in
their thinking as they negotiated the inclusion of nanoscale science and technology into the curriculum.

For example, data that inform the first sub question *do teachers demonstrate scientific content knowledge gains in response to the 2012 Project NANO summer workshop?* provided a description of each participant’s entry point and content knowledge gains into the process of learning about nanoscale science. The sub question, *of the nine “big ideas” in nanoscale science and technology, which are the big ideas that teachers choose to teach in their Project NANO unit and why?* provided the opportunity to develop a description of specific pedagogical reasons why teachers chose to frame their units on particular big ideas in nanoscale science for their first effort to integrate nanoscale science into the curriculum. This descriptive baseline of teachers’ content knowledge and PCK related to nanoscale science and technology, albeit quite incomplete, provided a basis of comparison to triangulate with multiple sources of teachers’ reflective data captured throughout the unit implementation and reflection cycle as teachers learned technical and developed pedagogical solutions for common problems of practice. The resulting description also informs the sub question, *how, if at all, do teachers’ metastrategic thinking and PCK change between the summer workshop and the reflection period following the implementation of the Project NANO unit of instruction.*

**The Context of the Study: Project NANO**

The context of this descriptive case study was a collaborative teacher PD program involving eight local school districts, two private schools and two departments in a university located in the Pacific Northwest of the United States. Project NANO has been
developed over the past 3 years by two veteran high school chemistry and biology teachers, a veteran Professor of Geology and me, a faculty member with a university-based Center for Science Education and Graduate School of Education at the time of the study. The collaboration is designed to establish a sustainable university-based program to prepare and enable K-12 educators to effectively use research grade microscopes in their science classrooms to improve student engagement and understanding of scientific concepts and processes.

The collective efforts of Project NANO have created a design-based teacher PD model that involves supporting the delivery of teacher-developed units of instruction, as well as the evaluation of the effectiveness and continuous improvement of the unit plan to support student learning. Project NANO coaches support the integration of supplemental datasets that teachers can access through an on-line databank to reinforce the use of microscopes to underscore the concepts of size and scale and the connection between form and function of matter at the microscopic and nanoscale.

Program participants are supported for one academic year with a one-week, eight-hours per day summer workshop, individual classroom coaching prior to and throughout the implementation of the Project NANO unit of instruction and the opportunity to borrow the Project NANO toolkit. This toolkit includes a table-top scanning electron microscope (Phenom), a research grade compound microscope (Leica) and microscope supplies such as glass slides, stubs and specimen mounting materials.

Project NANO is designed with the following instructional goals that are consistent with those of the NCLT teacher PD program at Purdue University:
Science:

- Provide grade 6-12 science teachers with an enhanced understanding of nanoscale science and technology;
- Enhance teachers’ awareness of the connections between nanoscale science and technology and the traditional scientific disciplines of chemistry, physics, biology, earth and space science, integrated science and mathematics;
- Train teachers in techniques for using a scanning electron microscope, a high powered compound microscope and associated software such as National Institute of Health freeware, Image J used to manipulate and analyze images for presentation;
- Introduce the nine big ideas in nanoscale science (Wansom, Mason, Hersam, Drain, Light, Cormia, Stevens, & Bodner, 2009), as identified through consensus at a series of National Science Foundation supported workshops in 2007.

Pedagogy:

- Enhance teachers’ knowledge and skills for using inquiry-based methods (such as the role of evidence and explanation in inquiry) for teaching nanoscale science;
- Explicitly teach and model teaching strategies such as cyclical rotation through laboratory stations, formative assessments and differentiation strategies;
- Promote reflection on salient issues involving teaching and learning through inquiry;
- Provide guidance and support for the development, implementation and refinement of units of instruction and individual lessons developed through Project NANO;
- Provide a program website as a vehicle for program participants to share their lessons and reflections, and contribute to the development of an annotated databank of images and curricular resources;
- Provide the opportunity to pre-service teachers to do their student teaching and student teaching work samples with a cooperating teacher who participated in Project NANO over the past 3 years;
Facilitate explicit dialogue among participants and the Project NANO team around how Project NANO fits within a proficiency-based education framework (Project NANO planning document, 2011)

**History of Project NANO.** In the summer of 2008, nine teachers agreed to use the Phenom scanning electron microscope (SEM) and research grade, high-powered light microscopes in their classrooms. Collectively, these teachers represented all of the disciplines of science taught at the secondary level in Oregon (e.g., biology, chemistry, physics, ecology, earth and space science and integrated science). A few of these teachers also taught upper division high school courses in mathematics, including statistics. A disciplinary faculty member from the department of Geology worked with those nine participating teachers and the Center for Science Education faculty to determine how light and electron microscopes could be used in teachers’ classrooms as a means to expand and reinforce the application of students’ inquiry skills and introduce the concept of nanoscale science into secondary level science classes. The group then worked to identify secondary science curricula ideally suited for using microscopes to improve instruction of concepts that are typically difficult for many students to conceptualize. This work formed the foundation of a databank of microscopic and nanoscale images (photo micrographs), narrative interpretations of images and sample instructional unit-plans developed by course participants. These materials formed the basis of materials used as examples for subsequent years of summer teacher PD workshops.

Two teachers in this group were particularly excited about the potential of this project to improve student learning outcomes in science and to provide support for the integration of nanoscale science and technology into the curriculum. These two veteran
high school chemistry and biology teachers agreed to receive additional preparation and pilot the instructional units that they developed in the workshop in their own classrooms. They intended to draw on this experience not only to update their own teaching practices, but also as preparation to co-instruct future summer Project NANO courses and provide teacher participants with coaching support during the academic year to help teachers to implement and examine their own Project NANO units.

This experience led to (a) the establishment of units of instruction which fit within existing curricula used in area schools and address school district, state and national content standards; (b) the pilot testing of these units of instruction in the teacher’s high-school classrooms using the university’s Phenom Scanning Electron Microscope and a Leica research-grade optical microscope; and (c) data-driven refinement of the summer workshop in which in-service and pre-service K-12 teachers learn to use the Phenom SEM and Leica and design a 2-week unit of instruction to teach inquiry-based science. These refinements also established the following learning targets for teachers in the workshop:

The Learner will have knowledge and understanding of:

- The difference between a light microscope and a Scanning Electron Microscope (SEM);
- The mechanics of a SEM;
- Safe and correct use of a desktop SEM to capture high quality images;
- How Science, Technology, Engineering and Mathematics (STEM) standards can be taught using the project NANO toolkit;
- Size and scale at the nano level (nanoscience, nano-properties, etc.);
• The CoRe and PaP-eRs approach (Loughran et al., 2006) to capture teachers’ narratives of their thinking during the development and implementation of the Project NANO lesson.

The Learner will be able to:

• Prepare samples for examination using both the optical microscope and the SEM;
• Capture an image digitally using an optical light microscope and desktop SEM;
• Use Image J (a free computer software application) to label, measure, and correct images;
• Create a scale bar for reference and measurement purposes;
• Safely and effectively implement the use of technological tools in a classroom with 20-40 students

(Project NANO planning document, 2011)

Based on the belief that the content of a PD workshop is most useful when it focuses on, “concrete tasks of teaching, assessment, observation and reflection” (Darling-Hammond & McLaughlin, 1995, p. 598), rather than abstract discussions of teaching, an integral part of the Project NANO summer workshops involve teachers in developing a unit of instruction that they will use to teach an approximately two-week unit of instruction during the upcoming school year. The development of this instructional unit plan is scaffolded into three activities: first, teachers work in groups or pairs to identify the learning objectives, as well as the big ideas in nanoscale science and cross-cutting concepts they will use as the foci of their unit plan in such a way that meets science content standards and fits logically within the science course. Second, teacher participants work in the laboratory to develop scientific inquiries using the Leica and SEM to develop, test and discuss an authentic research experience. And third, teachers
collaborate to fill in a Content Representations table and use this information to inform
the development of their instructional unit plan. Content Representations tables will be
described below. In some cases individuals created their own discrete unit plan but for
the most part, teachers worked collaboratively in pairs or groups to create shared unit
plans using the interactive unit planning template posted on the course website.

I begin with a description of the first activity. Initially, teacher participants work
in groups to conduct background research including analyzing sample lesson plans
provided by past program participants to generate ideas and think about the elements of
their own units of instruction. Teachers identify the potential unifying concepts to frame
the unit, cross-cutting scientific concepts and processes as well as possibilities for how
topics could be framed around the big ideas involved in the unit, promising approaches
for scaffolding such concepts, and probably methods to integrate scientific terminology
and classroom work to be organized.

For the purposes of this PD and study, the term unifying concepts refers to ideas
that connect different areas of science in deep and meaningful ways (NSTA, 2010c). For
example, concepts such as energy, patterns, systems, models, interaction and change,
form and function are all unifying concepts that bridge all of the disciplines of science.
This term is very similar to the term cross-cutting concepts that is currently used in the
NRC Framework of K-12 Science and the Next Generation Science Standards, defined
as:

The themes of concepts that bridge the engineering, physical, life and earth/space
sciences; in this sense they represent knowledge or knowledge about science as a
way of knowing. As such, the cross-cutting concepts are very important for addressing the science literacy goals.  
(NRC, 2012, p. 3)

Examples of some cross-cutting concepts provided in A Framework of K-12 Science are:

1. Patterns
2. Cause and Effect: Mechanism and Explanation
3. Scale, Proportion, and Quantity
4. Systems and System Models
6. Structure and Function
7. Stability and Change

(NRC, 2012, p. 2)

The term big ideas refer to ideas that have cross-cutting themes providing students with powerful ideas to help them to understand complexities of the natural and built world (NSTA, 2010c). As mentioned in Chapter Two, the nine big ideas in nanoscale science established by an NSF sponsored committee are: “size and scale, structure of matter, forces and interaction, quantum effects, size-dependent properties, self-assembly, tools and instrumentation, models and simulations and science, technology and society” (Stevens, Sutherland et al., 2009, p. 3). Further, “the term learning objective contains a verb (action) associated with a cognitive process and an object (usually a noun) that usually describes the knowledge or skill a student is expected to acquire” (Anderson & Krathwohl, 2001, p. 4). For example, a learning objective written by a Project NANO teacher who teaches sixth grade science reads “students will learn that
changes at the nanoscale can affect macro processes over time; specifically that erosive and depositional processes are analogous to destruction and construction on the nanoscale” (Project NANO participant’s unpublished Content Representations table).

Next, after getting ideas from the sample units of instruction and sorting through the possibilities they have considered, participants negotiated within their pair or group to choose a scientific unifying concept and three to eight learning objectives including one or more of the nine related big ideas in nanoscale science as the foci of the instructional unit they designed. All of the teachers drew on the Oregon state standards to develop their units and some draw upon materials provided at the workshop such as the *Uncovering Student Ideas in Science* series (Keeley, 2005), as well as the AAAS Atlas of Science (1994) concept maps to find ideas for learning objectives and big ideas, ways the concepts in the unit relate to one another, ideas for how to embed formative assessments into the unit.

Teachers then engaged in a scientific inquiry process as learners to investigate their own questions. The pedagogical intention of the workshop was that teachers experienced the inquiry process in much the same way their students may experience the process using the microscopes. They developed a testable inquiry, converged on assumptions with regard to how best to acquire data and determined the consequences of those assumptions, learned how the microscopes work and how to use them effectively, optimized data acquisition with different tools, and analyzed data quantitatively using a National Institute of Health freeware program, *Image J*. This process in the laboratory was essentially one of building their PCK and rationales for structuring their units of
instruction in such a way as to support the development of students’ higher order thinking abilities.

As teachers received guidance to test out a series of lab activities, they increased their abilities to anticipate how students may experience the inquiry cycle. By experiencing the natural cycle of the inquiry process, including moments of success and disequilibrium, teachers began the process of figuring out what questions students are likely to have when using the microscopes—questions either about the technology itself or the specimens they examine—and barriers and limitations that may need to be negotiated to optimize student success.

By the conclusion of the workshop, teachers then worked to refine their units with members of their group or pair and their Project NANO coach in preparation for implementation with students for the first time. Teachers reflected on their units of instruction through a guided process called *Content Representation (CoRe)*, and *call-out reflections* to be further described below. They also used this reflective process to record how students respond to specific lessons and activities, further building their PCK as they consider ways to improve student experiences throughout the unit and in preparation for teaching the unit again next year.

**The Research Paradigm**

This study is rooted in the tradition of the post-positivist research paradigm. According to the post-positivist perspective, knowledge cannot be divorced from ontology and personal experience. For the purposes of this dissertation, the term *ontology* is defined as one’s view of social reality (Grix, 2004). Rather than espousing dualistic
thinking, a post-positivist approach is interpretive with an emphasis on discerning multiple subjective meanings (Henriques, Hollway, Urwin, Venn, & Walkerdine, 1998). The post-positivist paradigm epistemology (or view of how one acquires knowledge) resists reductionist and mechanistic modes of interpreting phenomenon and, instead, embraces the idea that the subjective is a valid form of knowledge. Thus, from a post-positivist perspective the role of the researcher is that of a learner rather than a testing role.

In this role of the learner, instead of seeking to discover objectively hidden truths in a participant’s mind, the approach of a post-positivist researcher is to work with the participant to activate the respondents “stock of knowledge” (Ritchie & Rigano, 2001, p. 744) to socially construct a narrative. The researcher activates participant’s thinking by working to problematize topics, so as to explore the nature of a mental construct, not to come up with a universal solution but instead, the researcher offers thoughtful guidelines, principles and acknowledgements related to a specific topic or topics. Rather than asking one’s self “is this the truth?” the post-positivist researcher assumes the stance that valid knowledge claims are evidence that emerge as the participant’s interpretations arise and become intertwined with the researcher’s own interpretations. The fact that the evidence may involve conflicting interpretations is not viewed as necessarily problematic but rather produces an awareness of the complexity and historical contingencies of the interpretations of reality that we invent to discover social truths (Crotty, 1998).

Acknowledging the contradictions and tensions in the mind of participants allows for the potential to produce complex portrait of the participants’ thinking. This paradigm
requires that the post-positivist researcher assume a highly reflexive stance to conceive of and portray how meaning is constructed. The multi-dimensional narrative produced as a result of a post-positivist study is mix of concrete detail with analytic categories that connects the familiar with the unfamiliar (Patton, 2002).

**Role of the Researcher**

My current role in Project NANO is that of the internal evaluator and program co-designer. I drew on extant data collected for the evaluation for this dissertation research. That said, none of the data sources for the dissertation are unique to the dissertation study but are were collected for both the dissertation and internal program evaluation. The rest of this section describes how my experience with designing and implementing PD for science educators has informed my research approach.

Over the past six years I have worked with a university-based Center for Science Education to collaboratively design and implement science teacher professional development (PD) programs for in-service and pre-service teachers. Each of these PDs involved science teachers on special assignment (TOSAs) partnered with university-level science disciplinary faculty to teach science courses and workshops with follow-up coaching support.

As is the case with Project NANO, a common component of nearly every science teacher PD workshop or course offered through the Center for Science Education is an assignment to develop a unit of instruction that incorporates science content, technology and pedagogical strategies modeled and described in the workshop either by the workshop instructors or colleagues in the workshop. Course instructors encourage
teachers to employ a backward planning approach (Wiggins & McTighe, 2006) to lesson planning beginning with establishing learning objectives which involve big ideas in science including unifying and cross-cutting concepts (Keeley, 2005; Mundry, Keeley, & Landel, 2009) that frame the unit of instruction and then scaffolding lessons that provide the knowledge, skills and experiences necessary to learn scientific or engineering design concepts, processes and related unifying and cross-cutting concepts.

Groups of teachers collaborate to draw on the curriculum materials they brought with them to the workshop, materials provided through the workshop and their own experiences to collaboratively design a two-to-three-week unit of instruction using a locally designed unit planning template with columns labeled *science standards*, *knowledge, skills, experiences, pedagogical strategies, assessments*, and a calendar of lessons. Teacher participants engage in activities such as concept mapping (Novak, 1990) to display and discuss the relationship of concepts and visualize cross-cutting concepts. This concept map may also provide visual clues for how to developmentally sequence and scaffold the lessons in a way that fits logically within the course curriculum and allow for the teacher to be more sensitive and responsive to formative assessment feedback from students throughout the lesson cycle (Novak, 1990).

As groups or pairs of teachers work on these unit planning activities, I have observed that teachers typically have no trouble verbally describing how prior experience working with content and student feedback informs their ideas about how to frame particular content and how to order the presentation of particular topics for specific groups of students to improve understanding. Teachers working in groups typically share
stories of successful activities they have employed to teach connecting or cross-cutting concepts, especially ideas that bridge topics within their own discipline of science.

Participants eloquently describe strategies such as Sheltered Instruction Observation Protocols (SIOP, 1996) and techniques they have developed on their own to engage students. They discuss formative assessment strategies used to guide their teaching moves and inform students’ metacognitive processes about their own learning, giving clear examples of guiding questions they use to elicit student thinking to check for conceptual and procedural understanding and ideas for how to identify alternative concepts and to debunk common misconceptions in science and engineering that students hold.

However, in my past experience, when filling out the written unit of instruction template, teachers who spoke eloquently during the group planning discussions frequently did little more than list of series of activities they planned for the unit with no explanation as to the how these activities were sequenced and how the concepts addressed in the activities were scaffolded together to facilitate student learning. Furthermore, many participants left the assessment page of the template blank or they listed the unit test and grading policies rather than naming specific formative and summative assessment strategies they planned to employ and ideas related to how these specific student assessment strategies were intended to improve learning. Similarly, when colleagues and I conducted classroom observations of the lessons developed during workshops, during the de-brief conversations immediately after class teacher participants frequently had difficulty explaining the rationale that inspired particular instructional moves.
I submit that a reason for this difficulty is that teachers base a great many of their decisions on tacit knowledge or upon habits that they have not necessarily deeply examined (Ben-David & Zohar, 2009). I assume this claim to be valid based on my own observations and PCK-related literature (e.g., Loughran et al., 2006; Magnusson et al., 1999). Such literature supports my observations that it is often difficult for teachers to articulate knowledge based on long-standing experiences and habits, especially when the discussion is held out of context. This problem is compounded by the fact that most experienced teachers are not used to writing down their thoughts about problems of practice and describing their rationales for employing certain instructional strategies to address both common and non-so-common problems of practice (Winchow, 2010).

Although many teachers are aware that tacit knowledge gained by an accumulation of wisdom and knowledge from classroom experience both supports and confines teachers’ choice of strategies (Ben-David & Zohar 2009; Shulman, 1987), it is difficult for most to describe how their PCK frames reflexive choices made throughout the lesson. Also, the formal academic language used in university PD settings to describe teaching and learning strategies is often not necessarily the same language teachers typically use to articulate problems of practice; thus, communication between a university researcher and teacher is sometimes difficult (Ben-David & Zohar, 2009; Zohar, 2006).

In order to improve teachers’ abilities to bring tacit knowledge to the surface for discussion, I have found that it is helpful to set up a clearly contextualized situation where teachers and the researcher collaborate to pre-define features of the unit on which they intend to focus their awareness throughout the lesson design cycle (Knowles et al.,
Based on this awareness, the Project NANO team and I developed a set of criteria that guided my approach to examining teachers’ PCK used to develop and implement their Project NANO units of instruction. These criteria were the following: workshop activities should provide a comfortable way for science teachers to generate and record their ideas during the discussion about content and teaching strategies using familiar, everyday educational language and scientific terminology commonly used at the grade level(s) participants teach; the research approach should provide a systematic means for capturing evidence of teachers’ thinking during the implementation of the lessons; the approach should be flexible and not take up too much of a teacher’s time; and the approach should be a useful teaching tool for the Project NANO workshop and inform the follow up coaching process (unpublished Project NANO planning document, 2011). I was and remain also interested in facilitating the development of PD that provides a means for teachers to share their planning and reflective thought processes in a way that may be useful for colleagues to consider when approaching teaching very specific scientific topics.

At the 2012 American Education Research Association meeting in Vancouver, British Columbia, I found an approach that fits these criteria. A panel of presenters described Resource Folios, an approach to capturing and analyzing teacher reflective practice developed by researchers from Monash University of Australia. Resource Folios, designed to facilitate teachers’ reflective practice are composed of Content Representations (CoRes) and Pedagogical and Professional Experiences Repertoires (PaP-eRs; Bertram & Loughran, 2012; Loughran et al., 2006).
A Resource Folio engages teachers in developing a holistic overview of their PCK about teaching a particular topic or topics focused on three to eight learning objectives and in this case of this research, big ideas in nanoscale science associated with that topic. The CoRe aspect of the Resource Folio is designed for teachers to discuss, construct and record joint understandings of science content and pedagogical strategies of teaching and learning. PaP-eRs provides a framework for teachers to illustrate specific instances of PCK in a narrative form (Loughran et al., 2006) and in this case of this study, for the researcher to triangulate data such as surveys and classroom observations to describe teachers’ metastrategic thinking and PCK. In following section, I describe in greater detail the CoRe and PAP-eRs approach.

**Research Design and Methods**

This dissertation is a descriptive case study that emphasized qualitative methods using a design-based approach. Qualitative research methodology was pioneered by Anselm Strauss (December 18, 1916, to September 5, 1996), an American sociologist internationally known as a medical sociologist. Qualitative research involves gathering data in an effort to develop an in-depth understanding of human behavior and reasons that govern such behavior (Taylor & Bogdan, 1998). I chose to use this approach because qualitative methodology investigates the *why* and *how* of decision-making (Taylor & Bogdan, 1998). If I were merely interested in measuring teachers’ knowledge on a scientific topic, quantitative methods alone might have been appropriate. However, in this study I sought to examine complex relationships between a particular group of science teachers’ knowledge and their cognitive strategies for teaching.
For the purposes of this dissertation, I define *case study* research as a, “scholarly inquiry that investigates a contemporary phenomenon within its real-life context, when the boundaries between phenomenon and context are not clearly evident, and in which multiple sources of evidence are used” (Yin, 1994, p. 33). According to Creswell (1994), a case study is a holistic inquiry situated within a naturalistic setting for the purpose of investigating a contemporary phenomenon. In this case, the phenomena is teacher participants’ thinking about teaching particular science topics within the natural setting of the teacher PD workshop and the secondary classroom.

A qualitative case study will produce results for only the particular case(s) studied, and yet can be applied towards the development of a hypothesis around more generalizable social science questions (Taylor & Bogdan, 1998). In the case of this study, the goal was not to produce a generalizable hypothesis but to investigate questions related to how secondary teachers negotiated the inclusion of novel science and technology into the curriculum so as to understand teachers’ metastrategic thinking related to their PCK and to produce artifacts that will be helpful for science teacher PD. Although the focus of this study was target towards teacher professional development, materials produced by study participants will potentially be useful PD resources for pre-service teachers as well as in-service teachers preparing to teach content outside of their usual scientific content area and for experienced teachers to reflect upon the ideas of those that are pioneering the use of nanoscale science and technology in the secondary classroom.

Rather than attempting to control variables, a case study researcher – and also a design-based researcher–observes multiple variables at play within a specific context and
attempts to describe interacting relationships (Design-Based Research Collective, 2013; Yin, 1994). Design-based research is an interdisciplinary approach wherein researchers work in partnership with educators to refine teaching and learning practices based on studies performed in realistic classroom environments and interacting relationships between instructional activities and learners including the researcher(s), instructor and students. Case study research has the ability to embrace multiple ways of observing and interpreting these relationships including the ability to embrace multiple research paradigms, as well as qualitative and quantitative methods of data collection and analysis (Dooley, 2002). For example, I used grounded theory tools to analyze focus group data; however, this inquiry is not a grounded theory study because this dissertation is not attempting to create a grounded theory and because I employed the use of additional means to analyze and interpret data, including the use of quantitative instruments such as a scoring guide used to analyze instructional unit-plans and a rubric used to score and analyze pre and post content surveys.

This study was an intrinsic case study known as a *descriptive* case study (Creswell, 1994). A descriptive case study is a qualitative approach used to provide thick, rich descriptions of a situation or phenomenon with the intention of focusing the research on a particular aspect or set of parameters being studied (Yin, 2012). I chose to conduct an intrinsic rather than an instrumental case study for this dissertation research based on the fact that this study sought to describe how this particular cohort of teachers drew upon their metastrategic thinking and PCK when negotiating how to teach particular topics using technology within the social constructivist context of Project NANO. Unlike
instrumental case studies, this study is not designed to develop a theory or research instrumentation that will provide a universal understanding of best practices for teaching using scanning electron microscopy in the secondary classroom. Rather, the goal of this study was to provide readers with insights as to how teachers in this study approached problems of science teaching practice to integrate novel science content and novel technology into the curriculum.

**Multiple Case, Design-Based Approach.** The study used an intrinsic multiple case, design-based approach to examine teacher thinking. This combination of methodologies provided a complementary approach, which emphasized direct, scalable and concurrent improvements to Project NANO throughout the research process. Doing so was accomplished through the active involvement of the researcher working in close partnership with the program instructors/coaches and teacher participants in a “scientific processes of discovery, exploration, confirmation, and dissemination” (Kelly, 2003, p. 3).

Initially advanced by Brown (1992) and Collins (1992) as *design experiments*, design-based research represents an evolution in terms of a social science research methodology. Specifically, the approach posits synergistic relationships between program providers, participants and researchers to support systemic theorizing and improvement in both theory and in practice (Reeves & Hedberg, 2003). Design-based research has much in common with *intervention design* sometimes equated with *design experiments* in that the researcher documents and connects outcomes with development processes in authentic settings. However, design-based research differs from development experiments in that it tends to focus on a single project rather than comparing multiple
projects or interventions. As with *formative research*, the design-based approach involves testing iterative cycles of design, enactment, analysis, and redesign in collaboration between practitioners and researchers (Barab & Squire, 2004).

I recognize that there are researchers (e.g., Shavelson, Phillips, Towne, & Feuer, 2003) who point out that the design-based approach is challenged with some of the same issues that potentially influence the validity of case study research. For example, Shavelson, Phillips, and Feuer pointed to the tension found between doing research that will report on “locally valuable innovations [and] globally usable knowledge for the field” (Design-Based Research Collective, 2013, p. 7). Nonetheless, I think that although descriptions are highly contextualized and much care should be taken to not claim transferability of findings, design-based research can lead to the development of knowledge that can be used in practice and can inform practitioners and other designers based upon the reader’s own determination of usefulness.

What makes this study a *multi-case*, design-based study is that this study includes two groups: the entire group of 23 teachers and a sub-group of 14 participants. First, I began by analyzing and reporting the metastrategic thinking and PCK of the entire group of 23 teacher participants developed from pre and post survey results, participants’ CoRe narratives, their units of instruction, classroom observations, and other relevant observations captured in the researcher fieldnotes. Second, I analyzed and reported on the thinking of a sub-group of 14 teachers who completed the implementation and reflection cycle within the data collection period. The description of the sub-groups’ thinking was developed from the CoRe call-out reflections (to be described below), seven sets of
classroom observations and extensive fieldnotes, four individual interviews and a focus group involving nine participants. Figure 4 depicts this design:

**Figure 4.** Data sources for the entire group and sub-group of participants.

In addition to the data reported in Chapter Four, there are four Resource Folios for individual teacher participants who are part of the sub-group of 14 included as Appendix items A through D. These Resource Folios present the same data analysis as that of sub-group of 14, but with more descriptive detail of the actual artifacts generated by the teachers themselves such as their CoRes, call-out reflections, units of instruction and representative teaching materials and the research analysis. The four Resource Folios are included for two reasons: to provide more complete details on four teachers’ thinking
about how they approached integrating nanoscale science to teach particular topics in
science and to provide readers with deeper insight as to how data were analyzed and
interpreted.

Participants

This dissertation study involved the 2012 cohort of secondary teacher participants
in three sections of the Project NANO summer teacher PD workshop offered in June and
August of 2012. Each workshop was taught by the same co-instructors and involved a
separate group of teacher participants. The workshops involved a total of 32, K-12 in-
service teachers and 12, pre-service teachers; however the unit of analysis for this study
is a group of 13 males and 10 female (n = 23) secondary level in-service teachers from
the 2012 Project NANO cohort who agreed to participate in the study.

All 23 of the study participants reported in a survey given at the beginning of each
workshop that they teach science as inquiry at least part of the time. Only five of the
teachers had any prior personal exposure to an SEM, and of that number, two worked
with an SEM in a research capacity, two worked with an SEM as a student for a
laboratory-based class project and one worked with an SEM both in a class and as a
researcher. Table one summarizes the background information for the 23 participants
captured through a demographic survey administered at the beginning of each workshop.
Table 1

Project NANO 2012 Teacher Cohort’s Background

<table>
<thead>
<tr>
<th>Do you teach science as inquiry?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
</tr>
<tr>
<td>No</td>
</tr>
</tbody>
</table>

Do you have any experience working with a scanning electron microscope in any capacity?

| Yes      | 5  |
| No       | 18 |

If you answered yes to the last question, please check all that apply

- In a research capacity | 2
- As a student          | 2
- In a demonstration in a class or at a conference | 2

Each discipline of science taught at the secondary level (i.e., chemistry and biology, ecology, middle school sciences and physics) is represented by the group of 23 science teacher participants, two of whom teach more than one discipline of science. Slightly over half of the participants teach at the high school level (56%), and 44% of the participants teach middle-level science (see Figure 5).
Slightly over half of the teachers in the program taught science using instruments with a digital interface prior to joining the project this summer as depicted in Figure 6:

*Figure 5. Number of participants by scientific discipline.*

*Figure 6. Survey data demonstrating the number of teachers who teach using digital instruments.*
It is interesting to note this breakdown by discipline. The largest group of teachers who taught using instruments with a digital interface are high school biology teachers; six biology teachers answered yes and three answered no to the question do you currently use scientific instruments with a digital interface in the courses you teach? When asked what types of instruments they used, biology teachers replied that they used Vernier probeware and software, Global Positioning System (GPS) units, and digital balances. They also listed an assortment of computer-based simulations, models and analytical tools. A few career changers also brought instruments to their classroom such as a digital microcentrifuge from their previous work and one of the teachers described a digital colony counter he uses with students that a student in his class developed as part of a science fair project. Six chemistry teachers in the group were split with three answering yes and three answering no, that they did not use digital instruments in the classroom prior to involvement in this program. All of the chemistry teachers who said yes on the survey reported that they use Vernier software and technology and computer based simulations, models and analytical tools as part of their teaching practice. The middle-level teachers were also split with five answering yes and five answering no to the question and two who left the question blank on the survey. When asked, the middle-level teachers who said yes to the question report that they also used Vernier probeware and software and computer-based analytical and modeling software. One of the three physics teachers replied that he does use instruments with a digital interface. When asked, this teacher reported that he uses Vernier technology such as probes to measure force and motion, computer-based analytical and modeling software and instruments that he brought to the
classroom after leaving a long career in the field of engineering such as a materials stress and strain analyzer.

The survey data also indicated a significant spread in terms of teaching experience in the main discipline of science that the group of 23 participants currently teaches. The majority of the group, or 16 of the participants, fall between six and 10 years of experience teaching the scientific discipline(s) that they currently teach; at the extremes, two are early induction novice teachers (with less than three years of teaching experience) and five teachers have more than 10 years of experience in their disciplines.

The survey also asked the teachers to report on the number of laboratory-based science classes they have taken in college (at any time). Thirteen of the high school teachers and six of the middle-level teachers have taken laboratory-based science college courses. Four teachers reported that they have not taken laboratory-based college level courses. The majority of the cohort or 82% have taken seven or more classes. Twelve teachers or 52% have taken over 10 lab courses in science. Nine percent have taken four to six laboratory-based science courses and only one teacher has taken one to three lab-based science courses. Also, 12 middle-level and high school level teachers wrote in the margins of the survey that some of the laboratory based science classes they took did not relate directly to the discipline they currently teach or have ever taught.

**Sub-Group of 14 Participants.** The sub-group of 14 teachers was selected on the basis that they completed the unit implementation and reflection cycle within the data collection period. This sub-group is comprised of nine males and five females. Ten member of the sub-group teach middle-level integrated science and four teach high
school science (biology, chemistry and engineering design). Further details related to the genders and grade levels that participants teach are depicted in Figure 7.

![Figure 7](image)

**Figure 7.** Gender and level of experience of teachers in the sub-group.

**Participants Who Developed the Four Resource Folios.** Of the sub-group of 14 teachers, I decided to compile Resource Folios for two novice teachers with less than three years of teaching experience and two veteran teachers with greater than five years of experience teaching in the primary discipline in which they taught. Table 2 presents a brief summary of background information for each of the four participants I selected to compile Resource Folios. I assigned pseudonyms to each teacher to protect the identity of the participants.
Table 2

*Background of the Four Teachers with Resource Folios*

<table>
<thead>
<tr>
<th>Participant Pseudonym</th>
<th>Science Courses that he or she teaches</th>
<th>Years teaching in the primary disciplines of science he or she teaches</th>
<th>Number of college level science classes</th>
<th>Currently uses scientific instruments with a digital interface to teach</th>
<th>Teaches science as inquiry</th>
<th>Experience working with an SEM prior to this workshop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Michelle</td>
<td>High School biology &amp; chemistry teacher</td>
<td>1-3 years</td>
<td>7-10 classes</td>
<td>No</td>
<td>Yes</td>
<td>Yes, as a student &amp; as a researcher</td>
</tr>
<tr>
<td>Paul</td>
<td>High School Chemistry</td>
<td>1-3 years</td>
<td>&gt;10 classes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Tim</td>
<td>High School Engineering Design &amp; Physics</td>
<td>5-7 years</td>
<td>&gt;10 classes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Annie</td>
<td>MS Science</td>
<td>11-15 years</td>
<td>4-6 classes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

I chose a novice high school biology and chemistry teacher (See Appendix D, Melissa) in her second year of teaching because I noticed that the majority of the teachers designing life science units focused on learning objectives related to natural selection and adaptations and I wanted to provide a more in-depth description of how this teacher approached navigating the inclusion of nanoscale concepts into her evolution unit. I chose this particular biology teacher because she is the only teacher in the entire group of participants that has prior experience working with an SEM both as a graduate student and as a laboratory scientist and I was curious as to whether or not her prior ability to
navigate the use of this technology influenced her thinking and the development of her PCK.

Another reason I chose this particular teacher is that she implemented a Project NANO unit in both chemistry and biology classes whereas the rest of the group of 23 teachers only taught a Project NANO unit in one discipline of science. She designed her own unit for her biology class and then decided to draw upon a chemistry unit developed and refined over a three-year period by one of the course instructors/coaches on percent composition for her chemistry class. I was interested in examining her thinking about how she negotiated implementing someone else’s unit of instruction and determining whether or not there were differences between how she thought about teaching the nanoscale science unit in her chemistry verses her biology class.

I chose the novice high school chemistry teacher entering his second year of teaching (see Appendix A, Paul) because I understood that he would be teaching the unit with two separate classes that are organized by ability groupings as a result of a mathematics exam that the students took on the first day of school. I was interested in learning about how he thought about his unit with respect to each of the two groups of students.

I chose the middle-level teacher who had greater than 10 years of teaching experience (see Appendix C, Annie) because she said that she developed the unit “from scratch” and that she framed the unit around learning objectives that she does not typically teach her seventh grade students. Annie said that she will need to begin including in her practice because A Framework of K-12 Science (NRC, 2012) and the
Next Generation Science Standards (Achieve, 2013) require that she cover topics that relate to two of her learning objectives: natural selection and adaptation.

I selected the high school physics and engineering design teacher (see Appendix B, Tim) for three reasons. First, he is a seventh year teacher who left a 20-year career as an engineer to enter teaching. Second, he is one of only three physics teachers in the group of 23 participants and third, he said that he designed his unit as a supplemental unit to the Project Lead the Way engineering curriculum. I was curious as to how this teachers’ prior experience working with electron microscopy and engineering design would translate into his classroom practices and I wanted to know more about his rationale for how he sequenced his unit within the Project Lead the Way curriculum.

In the interest of full disclosure, I have known one of the high school teachers (Paul) and the middle-level teacher (Annie) in a professional capacity for more than five years. Paul graduated from the Masters in Science Teaching Program I coordinated and he also took two classes that I taught as part of his graduate level coursework. He also worked closely with me and a disciplinary science faculty member for his thesis research. The middle-level teacher, Annie, was involved in a teacher-as-researcher program I coordinated three years ago and she also participated in three teacher PD science-content based courses that I taught or co-taught.

The prior relationships that I have with two of the four teachers I have selected out of the group of 23 for closer analysis potentially benefited the study in a number of ways. One possible benefit was that over the years of collaboration, these teachers and I developed a sense of trust and an ability to clearly communicate with one another.
Because we did have an established foundation of trust and they knew that my role in Project NANO was to gather authentic descriptive data of their thinking, they said that they were not worried that I would think poorly of their teaching abilities or otherwise judge them as a teacher. Another potential benefit is that because I taught research methods and science inquiry courses that these teachers participated in, I knew that they had been exposed to educational research methodologies and the language of the post-positivist research paradigm. I also knew that these teachers were and are deeply familiar with the learning theories that frame this study (social constructivism and social learning theory) and the PCK framework based on the fact that we participated together in several class discussions and private conversations that relate to these theories over the years. Therefore, both of these teachers had a good sense of what type of data that I was looking for, understood the value of telling me what they really thought for the purpose of informing and improving the program and said that they were able to speak fluently about their thinking to a greater degree than may have been the case for teachers who had not developed this familiarity with the key concepts and language used to describe ideas related to this study.

I also recognize that these prior relationships may have some potential negative effects on the study. For example, because two of the four teachers I examined more closely did have a close professional relationship with me and others in the University departments I work for, they expressed that they felt that it was important that Project NANO be a success. This enthusiasm for the success of the program may have motivated the teachers to mask their true feelings about particular aspects of the program that they
thought to be less supportive of their cognitive development in order to make Project NANO appear to be more successful than it really was or is. Prior to reading their call-outs and hearing their reflections during the interviews and focus group, I held some concerns that they may simply tell me what I wanted to hear. However, experience taught me that based on our mutual sense of trust and desire to correctly inform the improvement of the program, each of these teachers were forthcoming to the point of being what I would describe as being brutally honest in comparison to their colleagues in the program. Moreover, I believe that these potential issues were mediated by the inclusion of multiple measures used to elicit and analyze their thinking; nonetheless, it was a potential problem I was aware of throughout the data analysis and reporting process.

Another potential drawback was that several teachers in the cohort who know me from past PD experiences where I served as either a program coordinator or co-instructor are used to expecting me to solve programmatic issues in my role as course instructor and/or program coordinator. It may have been difficult for these teachers to shift their perception of my role to that of an evaluator and researcher whose job it was to report data to the program staff rather than being the person responsible for actually solving technical problems. For example, during classroom observations I was repeatedly asked if I could go to the store to pick up more thumb drives to capture images when students either forgot to bring their thumb drive or the ones they brought with them would not work. Because I said that I could not leave an observation mid-stream to go to the store, this may have caused some confusion among the participants who knew me from the
past. However, given that I conducted multiple observations in each classroom I visited, teachers adapted to my new role, thus this problem was resolved.

**Data Collection Methods**

The data sources for this study were artifacts generated by groups or pairs of teachers during the summer workshop, reflective artifacts generated by individual teacher participants throughout the lesson cycle, and information generated through interviews with a subset of teachers’ and my own observations. The research employed the use of Resource Folios including CoRe and PaP-eRs elements as key artifacts used to examine teacher participants’ metastrategic thinking and PCK with the specific goal of understanding how teachers negotiated the inclusion of novel science content and novel technology into the curriculum.

This dissertation study was strongly influenced by the work of John Loughran, Philippa Milroy, Amanda Berry, Richard Gunstone and Pamela Mulhall of Monash University, Australia. The book *Understanding and Developing Science Teachers’ Pedagogical Content Knowledge* (Loughran et al., 2006) documented ideas learned through earlier studies that engaged teachers in developing Resource Folios as a means for communicating teachers’ PCK. These researchers drew upon Shulman’s definition of PCK as “the amalgam of content knowledge and teaching knowledge that makes that content better able to be understood through the particular teaching approach adopted” (Loughran et al., 2006, p. 289).

As is the case with studies conducted by Monash University researchers, the use of the Resource Folios in my study was meant to illuminate the thinking of a particular
group of teachers about how they negotiated problems of practice. The Resource Folio approach provided a framework to structure teachers’ thinking and a means for teachers to communicate their ideas about learning as they drew upon metastrategic thinking and built their PCK (Loughran, Milroy, Berry, Gunstone, & Mulhall, 2001).

Because this was a design-based study, I selected research methodologies intended to stimulate teachers to think, write and verbally discuss ideas about content, pedagogy and their ideas about how students learn particular scientific topics. The triangulation of data that resulted from the use of multiple instruments provided the means to capture teachers’ thinking as they shared “representations that portray [subject matter] to others in ways that might be useful in helping them to recognize and develop their own PCK of particular content” (Loughran et al., 2006, p. 289). As one teacher put it, “I’m not used to having to talk about my reasons for how I plan out units, so the CoRe and call-outs let me think about things I’d said earlier and respond to my own ideas, which is a lot easier to do than answering someone else’s questions.”

Among those who benefit from the dissertation study and in particular, the Resource Folios, is the Project NANO team of the principal investigator and the workshop instructors/coaches who were empowered with information about teachers’ thinking that informed their decisions about how to best plan the summer follow-up workshop with the 2012 cohort. These data also informed the next summer workshop that took place in June of 2013 and will inform academic-year coaching with both the old and new cohorts of participants. Beyond the program team and participants, readers may
draw their own inferences as to how the descriptions of teachers’ thinking reported here relate to their own contexts.

**A Description of Each Research Method.** The following methods were utilized for this study:

1. The Resource Folios,
   a. Teachers’ written CoRes developed by all 23-participants as part of the summer workshop (see Appendix E for the CoRe template),
   b. At the summer workshop and throughout the implementation of the unit and following the unit, teachers contributed to the assemblage of PaP-eRs. These artifacts are:
      i. Teacher developed units of instruction created during the summer workshop,
      ii. Teacher reflective notes in the form of reflective call-outs (Loughran et al., 2006) added by the 14 teachers in the sub-group throughout and following the implementation of the unit. Teachers either added their call-out reflections in writing directly to the CoRe table to notate his or her reflective thinking throughout the Project NANO unit lesson cycle or recorded reflections and emailed audio files to the researcher,
      iii. Focus group and individual interviews conducted with the 14 teachers in the sub-group following the implementation of the unit. The interview prompts asked teachers to think and talk about how he or she thought about how to structure and adapt their instruction to include nanoscale science and technology into the curriculum.

2. Pre and post surveys were used to establish baseline data on all 23 of the teachers’ knowledge of nanoscale science and technology and were used to determine whether or not teachers in the summer workshop demonstrated scientific content learning gains. Patterns of teachers’ responses on the surveys were also used as formative and summative assessment tools used by the course instructors/coaches to calibrate instructional support to teachers.

Figure 8 shows how the data sources informed the research question and sub-questions. I collected these data in the context of the internal program evaluation; therefore, all of these data were extant.
**Research Question**

How do teacher participants in the 2012 Project Nanoscience and Nanotechnology Outreach (NANO) program negotiate the inclusion of novel science and novel technology into the science curriculum?

- Resource Folios: CoRe and PaP-eRs

1. **Sub-question 1:** Do teachers demonstrate scientific content knowledge gains in response to the 2012 Project NANO workshop?  
   (All 23-teachers)
   - Pre & Post Surveys
   - Field notes

2. **Sub-question 2:** Of the nine "big ideas" in nanoscale science and technology, which are the big ideas that teachers chose to teach in their Project NANO unit and why?  
   (All 23-teachers)
   - Teacher developed unit plans
   - Focus group and individual interviews

3. **Sub-question 3:** How, if at all, do teachers' metastrategic thinking and PCK change between the summer workshop and the reflection period following the implementation of the Project NANO unit?  
   (Sub-group of 14 teachers)
   - Resource Folios
   - Fieldnotes

*Figure 8. Research questions and instruments.*
In the following section I provide descriptions of and the rationales for inclusion of each instrument and how these methods informed the questions.

**Resource Folios**

*Research Folios* that include the CoRe and PaP-eRs (Loughran et al., 2006) were employed as an approach to examine teachers’ metastrategic thinking as they negotiated the inclusion of novel science and novel technology (advanced microscopy) into secondary science curriculum. The Research Folio also served as the primary source of data used to examine teachers’ PCK related to specific topics teacher participants chose to teach for their Project NANO unit of instruction. Here, I describe the CoRe and PaP-eRs in greater detail.

**Content Representations (CoRe).** In the case of this research, the CoRe table provided an overview of how a teacher or group of teachers conceptualized a set of topics and how to teach specific learning objectives including big ideas in nanoscale science and engineering related to those topics. The CoRe table was used in Project NANO summer workshops to facilitate conversation between teachers as an initial step in planning their Project NANO unit of instruction. To begin, teachers were asked to consider a unifying concept (Keeley, 2009) to frame their Project NANO unit. For example, many of the life science teachers chose *evolution* as their unifying concept. Next, teachers choose three to eight learning objectives and one or more of the nine big ideas in nanoscale science or engineering related to the unifying concept to teach in their unit of instruction (see Appendix H for the Introduction to Resource Folios handout provided at the workshop).
For instance, several life science teachers who chose evolution as their unifying concept then identified a set of cross-cutting concepts as learning objective and big ideas. These topics were natural selection, biological morphological adaptations, phenotypes, genotypes, science inquiry, instruments and instrumentation, size and scale and the nature of matter. Teachers discussed and refined their learning objectives and big ideas and then entered their final choices into the CoRe table as column headers on the horizontal axis. On the vertical axis, each row had a question prompt that teachers discussed and then filled in the row of the CoRe related to that question with ideas that they agreed upon. Teachers were specifically prompted to share ideas on the CoRe table derived from each of their forms of knowledge as conceptualized in the PCK framework. They repeated this process for each of the learning objectives listed in the horizontal axis on the table.

The questions in the vertical axis are:

1. What you intend the students to learn about this idea?
2. Why is it important for students to know this?
3. What else you might know about this idea (that you don’t intend students to know yet)?
4. Difficulties and limitations connected with teaching this idea?
5. Knowledge about student’s thinking which influences your teaching of this idea?
6. Other factors that influence your teaching of this ideas?
7. Teaching procedures (and particular reasons for using these to engage with this idea)?
8. Specific ways of ascertaining students’ understanding or confusion about this idea?

(Loughran et al., 2006, p. 28)
The CoRe is not a validated instrument; therefore, the Project NANO team took liberties with the tool by adding questions specific to the program and this research. These questions are:

9. What are some common misconceptions students’ hold about this idea?
10. What are some difficulties and limitations connected with use of scientific instruments?
11. What are some learning opportunities that are made possible with the use of the SEM?
12. What knowledge about students’ thinking influences how you plan to integrate technology into the lesson?

(Project NANO CoRe table, 2012)

**Rationale for the questions included in the CoRe table.** These questions on the CoRe table were intended to stimulate teachers to consider fundamental ideas useful for planning to teach any topic. This process of considering these fundamental questions was repeated for each learning objective and big idea. In this way, specific content and PCK was described illustrating how the teachers approached teaching topics in a generalizable form that links the “how, why and what” of the content to be taught with what factors the teacher participants believe to be important in shaping the teaching and learning opportunities involved in the unit of instruction (Loughran et al., 2009).

**CoRe call-out reflections.** Teachers were asked to use the CoRe template as a reference to aid in their reflective practice throughout the Project NANO unit of instruction lesson cycle. Teachers either audio recorded or wrote their call-out reflections directly onto the CoRe table they developed during the summer workshop during and immediately following the implementation of the unit of instruction. In introducing the
call-out reflections during the summer workshop and follow-up email reminders, the researcher and instructors were very careful to be very general in describing the types of reflections the teachers might write because the Project NANO team wanted to avoid leading the teachers to write particular types of reflections. Rather, the team intentionally decided to allow the participants to make their own decisions as to what to reflect upon throughout the lesson cycle so that the research would authentically show evidence of teachers’ thinking. The only exception to this is that the researcher repeatedly requested that teachers draw on all five forms of knowledge as described in the PCK framework as they wrote their call-out reflections.

Rationale for the inclusion of CoRe call-out reflections. Teachers’ metastrategic thinking and PCK is often tacit knowledge that is difficult for teachers to verbalize or write, especially outside of the immediate experience in the classroom. Furthermore, teachers’ rationale for particular instructional strategies may in fact have been based on unexamined habits. By providing teachers with the opportunity to respond to their own writing in situ, I posited that teachers would be better able to access their own thinking in a way that illustrated participants’ patterns of thought relative to teaching specific topics with particular groups of students.

The purpose of requesting teachers to add call-out reflections to their CoRe tables was two-fold. The first reason was to provide a simple, quick method for teachers to revisit and update or add to their earlier thinking throughout the implementation-cycle of their unit. Teachers were asked to use their own CoRe to reflect upon their earlier thoughts and new ideas and then describe how their actual experiences informed their
thinking about aspects of the unit they designed in the summer. By reflecting upon their own writing in relationship to their actual lived experience, teachers had the opportunity to think about how well or poorly instructional strategies actually worked in the classroom and record ideas for how to improve upon teaching and learning specific topics found within the unit.

The second reason the Project NANO team requested that teachers record their call-out reflections is that these written or audio-recorded, call-out reflections provided the opportunity to capture teachers’ metastrategic thinking and PCK shared in response to their own authentic thinking rather than in response to the researcher’s’ prompts. The call-out reflections containing evidence of teachers metastrategic thinking and PCK informed the research question how do teacher participants in the 2012 Project Nanoscience and Nanotechnology Outreach (NANO) program negotiate the inclusion of novel science and novel technology into the science curriculum and the sub-questions, how do teachers’ metastrategic and PCK change between the summer workshop and the reflection period following the implementation of the Project NANO unit? and do teachers demonstrate scientific content knowledge gains in response to the summer 2012 Project NANO workshop?

Professional and Pedagogical Experiences Repertoire (PaP-eRs). PaP-eRs involve a collection of artifacts that overlap, inform one another and create the opportunity for a more nuanced understanding of teachers’ PCK. Loughran, Mulhall, and Berry describe PaP-eRs as narrative accounts of a teacher’s PCK for a particular piece of science content (Mulhall, Berry, & Loughran, 2003; Loughran et al., 2008).
PaP-eRs characterize teacher knowledge about specific aspects of teaching the topic content by providing “windows” into how such knowledge might inform effective classroom practice. A PaP-eR offers insights into a teaching and learning situation where it is the content that shapes the pedagogy. Each PaP-eR helps to illuminate the rationale that underpin teacher’s decisions and actions that are intended to help learners better understand the science content.

(Loughran et al., 2008, p. 1304)

The artifacts that I included as part of the PaP-eRs (to be described in more detail below) are: teacher developed units of instruction, researcher fieldnotes collected during the summer workshops and for the sub-group of 14 teachers who completed the implementation and reflection cycle by the conclusion of the data collection period, call-out reflections added by the participants to the CoRe table throughout the lesson, classroom observations, one focus group and four individual interviews. Next, I describe in greater detail the rationale for each of the items that will comprise the PaP-eRs used in this study followed by a description of each of the types of data sources.

Rationale for the choice of artifacts to include in the PaPeRs. I specifically chose to include the five artifacts I selected to be part of a collection of PaP-eRs based on descriptions found in the book *Understanding and Developing Teachers Pedagogical Content Knowledge* (Loughran et al., 2006, p. 24) of what the Loughran research group considers suitable materials to include in Resource Folios PaP-eRs. As described by Loughran et al. (2008), PaP-eRs may include teachers’ written and spoken reflections, classroom observations, and depending upon the purpose for collecting the PaP-eRs, may also include the students’ voices, (although this study does not include students’ voices). “Together in a Resource Folio, PaP-eRs bring the CoRe to life and offer one way of
capturing the holistic nature and complexity of PCK in ways that are not possible with the CoRe alone” (Loughran et al., 2006, p. 24). The collection of PaP-eRs used in this study illuminate for the reader the teachers’ process of how they came to see teaching and learning situations with new eyes as they reframed (Barnes, 1992) over a wider range of attention (Dewey, 1933) what goes on in the learning of particular science concepts and develop new PCK related to how to teach specific topics (Mulhall et al., 2003).

**Focus group and individual participant interviews.** One Project NANO focus group was held with a sub-group of nine teachers involved in the 2012 cohort who implemented their Project NANO unit by the end of February, 2013. The audio-recorded focus group entailed a one-hour interview held after this sub-group of teachers completed teaching their Project NANO unit of instruction. This interview was designed as an open-ended conversation (Morgan, 1998); the interview questions provided loose scaffolding for the conversation but did not consistently drive the direction in which the teachers choose to share their thinking. Indeed, after the first question, teachers in the focus group responded to and built off of one another’s descriptions of their thinking throughout the hour.

Four of the 14 teachers in the sub-group chose not to attend the focus group due to schedule conflicts or a personal preference to be interviewed one-on-one. In each of these cases, I visited teachers’ classroom after school and held a 45-60 minute audio recorded interview with each of the four individual teachers. The focus group and individual interviews contributed to the PaP-eRs portion of the Resource Folios by adding teacher participants’ narrative reflections on their rationales for their choices of pedagogical
strategies they chose to utilize in the Project NANO lessons and if their strategies did change, why they shifted and why they thought that they may change the lessons again if they teach the same or a similar unit in the future.

Three techniques were employed to prepare participants to reflect and communicate their thinking during the interviews. First, prior to each interview, I asked each participant to review his or her CoRe table and call-out reflections and note any new ideas that this review stimulated. The second technique was that I asked each teacher to bring his or her laptop computer loaded with blinded examples from their lessons or students’ work that would help to exemplify points they may make regarding how they designed and taught the unit. As it turned out, the majority of the participants did not bring examples of student work or lesson plans to the interview. The two teachers who did bring artifact to share chose to bring printed examples of student work and lessons to share and discuss during and after the focus group.

The third technique used in the interview was that the metastrategic thinking and PCK constructs were explicitly referred to throughout the focus group and individual interviews as a means to facilitate teachers sharing their PCK that informed their rationales that guided their instructional decisions. Again, teachers were repeatedly reminded to go beyond the simple question of how they teach a topic to the deeper questions reflect upon and describe what they know about the content, curriculum, student thinking, assessments and instructional strategies that informed their rationale that motivated their pedagogical choices and changes to their thinking, if changes did in fact occur.
Rationale for use of focus groups and four individual interviews. Earlier research into teacher PCK demonstrated the difficulty of realistically portraying teachers’ thinking in response to teaching and learning situations. In part this difficulty may have arisen because the earlier research tackled questions such as “How do you teach states of matter to your grade 9s?” (Loughran et al., 2001, p. 293) rather than probing the much deeper types of questions such as “What is it that you understand about the states of matter that is important to take into account when deciding how to teach it to this group of students?” (p. 293). Researchers such as those who developed the Resource Folios technique came to understand that vehicles of representation needed to be created that are capable of carrying the complexity of the portrayal of teachers’ content knowledge and PCK.

Researchers from Monash University interested in teacher reflective practice found that one PaP-eR, such as just the CoRe call-out reflections, is not enough data to illustrate the complexity of teachers’ knowledge about the content and how to teach particular topics (Loughran et al., 2001). Although written narrative descriptions typically portray insights that illustrate rich experiences, they may fall short of explicitly communicating meaning or rationale beyond generally describing a teachers’ practice or classroom activities (Loughran et al., 2001). The overlap, interplay, and the relationship between PaP-eRs in a content area are important for viewing the complex nature of PCK.

Similarly, inviting teachers to interact in a focus group with the researcher provides the opportunity for interplay between the various perspectives of teachers (Morgan, 1996) who are all negotiating the challenge of integrating novel science content
and technology into the curriculum for the first time. The format of the focus group situates the conversation in the context of describing direct applications of PCK. In this study, the group conversation was nuanced because the participants developed a strong sense of a shared context, yet participants retained awareness that their own unique metastrategic thinking and PCK informed their choices in ways that differed from that of their colleagues.

**Unit of Instruction.** On the second day of the Project NANO summer workshop, program participants were provided with an instructional unit planning template (see Appendix K) and a scoring guide (see Appendix L), (Becker, 2010) for the unit plan. The purpose of the unit planning template (Appendix K) was to ensure that teachers planned and communicated the knowledge, skills and experiences students will approach throughout the unit. The unit planning template also provided the opportunity for teachers to record their considerations for how they would facilitate the development of student learning communities throughout the units. Furthermore, the unit planning template instructions asked teachers to consider and share specific pedagogical strategies they planned to employ in the lesson such as assessments and differentiation teaching strategies.

The Knowledge, Skills and Experiences scoring guide (Appendix L) used for the instructional unit plan was also presented on the second day of each of the summer the workshops to establish a mutual understanding of the elements that should be described in the written unit plan. The cover page of the Knowledge, Skills and Experiences scoring guide describes each of the five components to be included in the instructional unit-plans:
knowledge and concepts, science inquiry and/or engineering design skills, student experiences and learning community and assessment of student achievement.

**Rationale for the inclusion of the unit plan as a source of data.** The units of instruction were included within the collection of PaPeRs because these data provided necessary background information related to the unifying concepts, topics, learning objectives and big ideas in nanoscale science teachers selected for each Project NANO unit. Furthermore, the teachers’ written units of instruction communicated the structure and instructional strategies employed in each unit of instruction. Because this research was focused upon understanding teachers’ metastrategic thinking and PCK related to teaching and learning specific scientific topics, details described by the participants in the unit-plans provided critical context for understanding and interpreting teachers’ thinking. The scoring guide provided a criterion-referenced assessment instrument for the researcher, instructors and participants to evaluate and discuss each element written in the unit of instruction.

Examination of the unit-plans informed the research question, *how do teacher participants in the 2012 Project Nanoscience and Nanotechnology Outreach (NANO) program negotiate the inclusion of novel science and novel technology into the science curriculum* and the sub question *of the nine “big ideas” in nanoscale science and technology, which are the big ideas that teachers choose to teach in their Project NANO lesson and why?* Throughout the data collection and analysis cycle, this baseline knowledge also provided critical markers key to recognizing instances of how teachers’ thinking changed (or not) between the summer workshop and throughout the
implementation cycle. Therefore, the unit-plans also provided useful evidence to inform the sub question, *how do teachers’ metacognitive and PCK change between the summer workshop and the reflection period following the implementation of the Project NANO unit?*

**Classroom Observations.** As the internal program evaluator, I conducted non-participatory classroom observations in a sub-set of secondary teacher participants’ classrooms. The decision as to which teachers in the cohort to observe was based on the evaluation plan to conduct four observations in the fall and four in the spring. Of these eight observations, I chose to select for this dissertation study the fall and early winter observations of teachers who scheduled to teach their Project NANO unit between September 2012 and January of 2013 so that I could complete this dissertation by the end of July, 2013.

Of the 14 teachers in the sub-group, I observed seven teachers who taught their unit during the fall term and early in the winter term. In each case, I conducted either four or five observations per teacher. Each of the first observations were conducted within the first two-days of the beginning of the unit, two or three observations were conducted in the middle of the unit and one observation was conducted on the last day of each of the seven teacher’s nanoscale unit of instruction.

For each of the classroom observations, I used a validated classroom observation instrument known as Electronic Quality of Inquiry Protocol (EQUIP), developed by Marshall, Horton, Smart, and Llewellyn (2009). The EQUIP instrument is part of the Inquiry in Motion program at Clemson University. According to the Marshall research
group, “The EQUIP instrument is designed to measure the quality and quantity of scientific inquiry-based instruction. This instrument does not measure all forms of instruction, only those that are inquiry-based in nature” (Marshall et al., 2009, p. 1). I selected this particular classroom observation protocol because the instrument allowed me to assign: activity codes ranging from non-instructional time to exemplary inquiry, organizational codes (whole class, small groups or individual work), a code for student attention to lesson (low, medium and high percentage of students paying attention), codes for the level of cognitive demand (receipt of knowledge, lower and higher order thinking, apply, analyze or evaluate and create), codes related to inquiry instructional components (non-inquiry, engage, explore, explain, extend, also known as the 5Es), and finally an assessment code (no assessment observed, monitoring, formative assessment, summative assessment). I also captured extensive fieldnotes as I followed each teacher around the classroom and noted what he or she did or said throughout each observation. When necessary and possible, I also noted students’ actions and words to provide context to the teacher’s actions and words.

Rationale for the use of classroom observations and the choice of EQUIP.

According to the developers of EQUIP, this protocol was:

…designed from the outset to (1) evaluate teachers’ classroom practice, (2) evaluate PD program effectiveness and (3) provide a tool to guide reflective practitioners as they strive to increase the quantity and quality of inquiry that they lead in their classrooms. The culminating four-construct (Instruction, Curriculum, Interaction, and Assessment) EQUIP is a reliable and valid instrument that meets these goals. (Marshall et al., 2009, p. 10)
In the case of this study, the use of the EQUIP classroom observation protocol provided a framework used to examine where each of the nanoscale units of instruction fell along the scientific inquiry continuum described by Marshall et al. (2009). I drew on the EQUIP scores and fieldnotes to examine specific evidence of how the units were designed and lessons were shifted during implementation based on each teachers’ PCK. Classroom observations provided an external perspective to that of the teacher participants’ to contribute to the development of a thick, rich description of how teachers drew upon their metastrategic thinking and PCK to negotiate the inclusion of novel science content and novel technology into the curriculum. This external perspective was important because it provided further contextualization for what the teachers communicated about their metastrategic thinking and PCK used throughout the planning and implementation cycle of the unit.

Another reason that I chose the EQUIP classroom observation instrument was because the overarching pedagogical approach taught and modeled in the summer workshops is guided and open-ended inquiry. Each of the unit-plans designed by the participants emphasized the scientific inquiry process, although there are differences in terms of where each unit lies on the continuum from teacher-directed, step-by-step laboratory activities to open-ended inquiry as described in the EQUIP framework (Marshall et al., 2009). Thus, EQUIP scores were useful to describe specific elements of the inquiry lessons in this dissertation study and also served as a tool for the Project NANO team to consider to inform coaching of the 2012 cohort and when planning the next PD workshops and future coaching sessions.
For example, the majority of the 2012 cohort of teacher participants taught guided inquiry units \( n = 18 \) of 23. Thus, the Project NANO team now understands that the majority of the instructional strategies discussed and modeled in the follow-up summer workshop should use a guided inquiry instructional approach to provide coherency with the majority of the participants’ experiences and expectations.

**Researcher fieldnotes and rationale for inclusion in the study.** Researcher fieldnotes from the summer workshops provided the researcher with a sense of context for ideas shared by participants in the study. As the internal program evaluator, I served as a participant-observer in each of the three summer workshop sections and hand-wrote notes throughout each workshop (see Appendix M for the format of the fieldnotes). As mentioned above, I also recorded fieldnotes during each of the classroom observations and then throughout discussions with each teacher prior to and immediately following each observation where I was an non-participant observer.

The rationale for including fieldnotes as a data collection strategy is two-fold. The first reason is that the teachers’ CoRe reflective writings referred to discussions and activities from the workshop or classes that were observed; therefore, the fieldnotes provided important contextual references that give more meaning to the ideas expressed by the teachers in the call-out reflections. The second reason is that fieldnotes assisted with efforts to maintain accuracy in terms of interpreting references teachers made during interviews to situations teachers’ knew that I had observed during the workshop and classroom observations.
For example, during the focus group a participant referred to difficulty she had experienced capturing quality images using the SEM and Leica during the summer workshop and changes she made to the student lab plan to accommodate for difficulties she had learned to anticipate. Indeed, this teacher’s students were observed experiencing similar difficulties throughout their own inquiry processes. The teacher vocalized following a classroom observation that based on her own lab experiences in the summer, she felt that she was ready to prompt students and ask guiding and even so-called funneling questions that directed students’ actions working with the SEM and Leica. Had this teacher not known that I had noted her lab experiences and struggles during the summer, she may have been less likely to have shared this aspect of her thinking during the classroom observation follow-up discussion.

The final rationale for the inclusion of fieldnotes in this study is that data from the classroom observation scoring guide and researcher fieldnotes taken throughout each observation were triangulated with the rest of the Resource Folios data and the pre and post survey data to inform the research question, how do teacher participants in the 2012 Project Nanoscience and Nanotechnology Outreach (NANO) program negotiate the inclusion of novel science and novel technology into the science curriculum and the sub question, how do teachers’ metastrategic and PCK change between the summer workshop and the reflection period following the implementation of the Project NANO unit?

**Project NANO Pre and Post Survey.** The Pre and post survey was locally designed as a formative assessment not included in the workshop grade. The survey was
co-developed and piloted during the 2011 Project NANO summer workshop and then further refined between the first and second workshops in 2012. The pre survey involved two sections; section one was a series of questions that asked about the participants’ scientific and teaching background and section two is content-based. The second section of the survey is a criteria-referenced assessment that measured individual participant’s level of mastery of very basic nanoscale science and technology knowledge in comparison to a pre-determined performance standard articulated in a rubric developed and refined by the course instructors and the researcher.

The pre and post survey involved a set of open-ended questions for the first section of the workshop. The same items were used for the pre and the post survey. The survey instrument was slightly changed between the first and second workshop; two multiple-choice questions were added to the survey and the phrase “mechanics of the instrument” was removed from an open-ended question. The revised pre and post survey was used for the second and third summer workshop. The same items were used for the revised pre and the post survey; in other words participants responded to the same set of questions on the pre survey and on the post survey.

The background data developed from section one of the pre survey was used to characterize the participants in the study in order to add to the rich description of those teachers and their prior experience related to nanoscale science and technology. The purpose of the content portion of the survey was to establish general baseline understanding of teachers’ knowledge bases related to fundamental nanoscale science concepts such as size and scale and use of technology, such as how an optical light
microscope works in comparison to how an electron microscope works, how to capture and manipulate images from a scanning electron microscope and how to use software to refine images for sharing. Both versions of the pre and post survey used for the 2012 workshops are found in Appendix F and the rubric is found Appendix G.

**Rationale for the inclusion of a pre and post survey.** The Project NANO team approached the creation and use of this survey instrument using a design-based methodology wherein the pre and post survey responses of the teachers in the first of the three workshop sections informed the refinement of the survey instrument and the scoring guide and also informed refinements to instruction provided to teachers throughout the second and third sections of the workshop. In turn, survey results from the second workshop informed refinements to instruction in the third workshop.

For example, the post survey data from the first section of the summer workshop revealed that the brief description of the parts of the instrument and how the SEM works offered during the workshop was insufficient for teachers to be prepared to answer students’ questions about the instrument. For the second session of the workshop with a new group of participants, the instructors added a PowerPoint lecture on the key parts of the instrument and how it works and repeatedly described the function of these parts while the teachers worked with the SEM.

Analysis of the post survey responses provided evidence that the participants in second session responded to the survey questions with much more discrete knowledge and many more correct answers following their participation in the workshop than the teachers in the first section of the workshop. Given this positive feedback, the course
instructors built upon the presentation and guidance provided in the second workshop and added to the program website a selection of videos and reading materials on the parts of the Phenom SEM and Leica and how each microscope works, which the instructors explicitly described when they described the resources on the website and how they may potentially be used to support instruction during the third workshop and in their follow-up coaching meetings. Recognizing the need to provide age-appropriate video instructions on the function and use of the instruments, a teacher participant later created a series of classroom videos to add to the Project NANO website.

Although the survey is not a validated instrument, the workshop instructors and I felt confident that the revised survey instrument has a higher level of validity than the old one did. The revised survey more accurately measured the desired learning target outcomes and it did so in a way that was helpful to inform the reflexive practice of the co-instructors/coaches during the workshop and coaching of individuals during the academic year.

**Data Analysis**

The process of data analysis was divided into three phases. The first phase involved the scoring and analysis of artifacts generated during the summer workshop that I called “influencing factors” for the units that the participants actually implemented as their Project NANO units of instruction. The second phase involved the coding and analysis of reflective artifacts that teachers generated in written and verbal form and the third phase involved triangulating data related to teachers’ metastrategic thinking and PCK. For the
purposes of this study I called the artifacts generated for the second phase of the data analysis “lesson incorporation.”

Figure 9 is a graphic outline of the data analysis protocol timeline followed by a description of how each set of data was coded or scored and analyzed. This graphic found on the next page is a visual depiction of iterative process used to analyze the data and construct categories of teachers’ metastrategic thinking and PCK:
Figure 9. Data analysis protocol.
Data Coding and Scoring

A variety of analytical tools were employed to interpret data in the study: a scoring guide was used to analyze the pre and post survey, a rubric was used to analyze the instructional unit plan, the EQUIP protocol was used to analyze classroom observation data and dialogical coding based on Charmaz’s (2006) approach to dialogical coding was used to analyze the CoRe, call-out reflections and interviews. To be clear, this is not a grounded theory study but rather a design-based descriptive case study that drew upon grounded theory tools to analyze some of the data. Because this was a design-based descriptive case study, I analyzed data as it was generated so as to provide rapid feedback to the Project NANO coaches throughout the dissertation study.

For example, I applied the rubric to score the pre and post surveys immediately after the teachers completed each survey and then performed a simple statistical item analysis to inform the Project NANO instructors’ thinking during the summer workshops. Similarly, following each of the three summer workshops, teachers submitted their CoRe tables and units of instruction which I immediately analyzed so as to provide timely feedback to the instructors/coaches. As each teacher submitted his or her CoRe call-out reflections, I analyzed teachers’ call-outs and added resulting categories, factors of thinking and thematic patterns to the growing compilation of data. Finally, within two-weeks of each interview and the focus group I transcribed the audio recordings and then coded each interview using a dialogical coding approach to analyze the data.
Here, I will provide a description of the dialogical coding and analysis of the CoRes, call-out reflections and interviews. I will begin with a discussion on dialogical coding and Grounded Theory.

*Grounded Theory*, is a method of qualitative analysis widely used in sociology, social work, nursing, education, and organizational studies (The Grounded Theory Institute, 2013). I drew upon Charmaz’s (2006) approach to using dialogical coding for the purposes of this study. Charmaz views grounded theory methods “as a set of principles and practices, not as prescriptions of practices” (2009, p. 9) that define a set of methodological rules. Rather than referring to her approach using the term grounded theory, Charmaz referred to her approach as *dialogical coding*. She approached the dialogical coding method from a symbolic interactionist theoretical perspective that assumes the use of the tools offer an interpretive portrayal of the world, not an exact picture of it (see also, Guba & Lincoln, 1994).

In the case of this particular study, the goal was not to claim that this dissertation would offer generalizable results, show causality or to generate theory but instead to present thick, rich descriptions of how this particular set of teachers involved in this study drew on, built upon and developed new metastrategic thinking and PCK to integrate nanoscale science and technology into curriculum to teach specific topics through their involvement in Project NANO during the 2012-2013 academic year. Rather than applying preconceived codes and categories, dialogical coding (Charmaz, 2006) fostered studying teachers’ words and cognitive processes themselves to develop representations of their thinking and to grapple with what these words and ideas mean.
Using the strategies described in Charmaz’s (2006) book *Constructing Grounded Theory: A Practical Guide Through Qualitative Analysis*, coding began with an initial section-by-section coding approach using action-oriented terms to start to conceptualize ideas found in the teachers’ words. Each section of text was determined based on the following rationale: the CoRe document is designed as a table with discrete cells. Teachers wrote their initial ideas and call-out reflections in each of these cells and I treated each of those cells as discrete sections to code.

The interviews and focus group discussion were transcribed with each speaker's turn separated into discretely labeled sections; each of these discrete sections was treated as a separate section to code. Using the NVivo software, I identified multiple codes (words) with the same meaning and then reduced the data by choosing one code that most accurately reflected the meaning that I thought was intended by the teacher for each code. Once I reduced the data to a set of initial codes, I focused coded the initial codes which permitted data to be separated, sorted and synthesized into categories, factors of thinking and thematic patterns of ideas (Charmaz, 2006). Next, I provide a more detailed description of how I analyzed each set of data.

**Data Analysis of CoRe Templates and Call-Out Reflections.** The CoRe template created by teachers at the summer workshop and the reflective call-outs written on the CoRe throughout the lesson cycle were analyzed using a grounded theory approach as described mainly by Charmaz (2006), and drawing upon guidance provided by Miles and Huberman (1994), Saldaña (2012) and Wolcott (1994) as needed. Because one teacher chose to audio-record verbal call-out reflections throughout the unit
implementation cycle, his recording was transcribed and added to the rest of the set of 14
call-out reflections for dialogical coding and analysis.

The initial analysis began with reading and rereading each CoRe and call-out
section-by-section and journaling analytical memos of ideas that I noticed in the data. In
keeping with Loughran et al.'s (2006) approach to entering researcher memos or codes to
each teacher’s or group of teachers’ CoRe table, I added a column to the right of each
learning objective column in the CoRe table where I inserted a memo or code for each
section. Some examples of codes that I developed and used are: complementary
technology, student engagement and debunking student misconceptions.

Next, I loaded each CoRe and call-out reflection initial code into the NVivo
program. I then closely examined each of the sections by looking at the codes I had
assigned to each section of the CoRe, including the initial writing and the call-out
reflections, and compared the assigned codes for similarities and differences (Saldaña’,
2012; Strauss & Corbin, 1998). For instance, I found that I had assigned the codes
alternative conception and student misconceptions and naive conceptions to different
sections of text. I re-read the text and determined that the codes had the same meaning,
therefore I reduced the number of codes by selecting one code, in this case student
misconceptions, to assign to sections that were initially labeled with one of the three
codes that held the same meaning.

The goal of this initial coding step was to remain open to all possible meanings
indicated by the data (Charmaz, 2006). In this cycle of initial coding, I looked for
elements of possible or developing categories of teachers’ thinking and noted them as
potential categories in my research journal. I did this partly in anticipation of the focused coding step and partly to maintain awareness of my own potential bias so that I could double check my notes and the final codes when I came to that step in the process and be sure that the codes I finally selected were based on the meaning found in the text itself and not simply my biased interpretation of the meaning of the text.

Next, I applied an approach known as “focused coding” (Charmaz, 2006, p. 57) to refine the initial dialogical codes. This is a process that entailed using the most significant codes to sift through the large amount of data found in the CoRes and call-out reflections. I established significance of codes by considering the frequency of codes and by looking for direct comments from teachers that highlighted the importance of particular codes. For instance, teachers said or wrote words such as "this is important," or "I learned that..." or "something to share with other participants that I found to be helpful is..." I also looked for codes that were developed from multiple forms of data. For example, I noticed during classroom observations and in multiple teachers’ interview comments, CoRes and call-out reflections that some teachers established specific roles for members of the student lab groups. Although only a few teachers established group roles or explicitly mentioned this instructional strategy, those teachers who did mention ideas related to clearly defined group roles repeatedly emphasized differences in student achievement in response to this instructional strategy. Hence, I determined that the codes related to group roles were significant.

After I established the significance of codes and reduced the initial data sets, I reviewed the resulting set of initial codes to look for categories of responses and thematic
patterns developed from the data. For example, some of the codes related to technical problems and solutions teachers developed as a result of their experiences. I grouped all of the codes related to technical problems together on a page and then I grouped all of the codes related to technical solutions together and then grouped the codes related to instructional strategies related to supporting students to problem solve technical challenges. I then used the concept mapping approach (Novak, 1990) and drew lines between codes that fit in these multiple groupings to gain a sense of the relationships between the codes.

Based upon my emerging awareness of the multiple forms of knowledge or PCK that informed teachers' thinking and the relationships between codes, I then reorganized and reanalyzed the data to develop a coherent synthesis of the corpus of it (Charmaz, 2006; Miles & Huberman, 1994). To do this, I created categories of metastrategic thinking and then grouped factors of thinking under each category of metastrategic thinking.

For example, I noticed that teachers wrote and spoke about multiple ideas related to the scope and sequence of the unit. They described how they thought about the fit of the selected topics and learning objectives with the larger curriculum cycle and developmental appropriateness for the grade level and discipline of science. To further examine such relationships, I color-coded each category and thematic pattern associated with each code related to the fit of the topic and developmental considerations teachers described and manually analyzed which factors of teachers thinking did or did not fit
under multiple categories as another way to develop an understanding of the relationships between the categories and factors of teachers' metastrategic thinking.

After achieving saturation of the data by considering many multiple ways in which to categorize the data and establish sets of factors of teachers' thinking under each category for metastrategic thinking, I revisited the original CoRes, call-out reflections and interview transcripts to identify and code forms of PCK associated with each thematic pattern using a structural lens rather than an open coding approach. The structural lens that I employed this time was the PCK construct. Recall that these forms of PCK I focused on are knowledge of the content, curriculum, instructional strategies, student thinking, and student assessment (Shulman, 1986; Magnusson et al., 1999). Finally, I completed the focused coding process by identifying and selecting representational quotations for each category and thematic patterns of PCK developed from the data.

In keeping with the tradition of the grounded theory and case study approach, I analyzed data on an on-going basis, informing both later data analysis and data collection (i.e., the classroom observations, informal discussions with participants, the focus group and individual interviews). In other works, this process of focused coding was not a linear procedure. As I developed the focused codes, they each inspired a return to look at the initial codes from a new perspective which informed the iterative development of new or refined initial codes and then, new focused codes. This step was critical to ensuring that codes accurately represented to the greatest degree possible what teachers meant to convey. The intention of this iterative approach to data analysis was both to improve the
accuracy of my interpretation of teachers' meaning and to add value to the teachers' experience of participating in the research as they built upon their own and one another’s metastrategic thinking and PCK and elaborated on ideas that they thought were important to consider. This was an important because, rather than building on my preconceived ideas about their thinking that may of unintentionally skewed the conversation away from what teachers wanted to emphasize or meant to convey, I was able to repeatedly ground discussions and analysis in what teachers' thought about and chose to share.

For example, during the first initial and focused coding round, I misinterpreted several teachers’ meanings when they said that they, “wasted class time with sample preparation and loading stubs.” By repeatedly revisiting the original, open-coded call-out reflections and interview transcripts and analyzing the context of the mention of the idea of wasting time preparing samples and then reflecting on the classroom observation fieldnotes, I came to understand that what teachers actually meant was that they should have asked students to prepare and mount samples on the stubs and slides prior to the arrival of the SEM in the classroom. In fact, teachers meant the opposite of how I first interpreted their words. They meant that sample preparation is an important procedure that should not be rushed and that by waiting until the SEM arrived to prepare and mount samples, the students did indeed rush through these procedures to ensure that they were able to access the SEM when their group rotation on the instrument was called.

This critical nuance in the teachers' meaning was not only important to ensure the accuracy of research; this nuance became very important information for the coaches to learn in a timely manner. In fact this corrected interpretation afforded the two
instructors/coaches to adapt their follow-up coaching of the 2012 cohort and the 2013 Project NANO summer workshops to emphasize activities in the unit that can be done in advance of the arrival of the instruments in the classroom so as to maximize time with the instruments in such a way that any of the learning objectives are not compromised due to time constraints associated with the Project NANO toolkit schedule.

The categories of responses developed from the CoRes data informed the research question, *how do teachers negotiate the inclusion of novel science content and novel technology into the curriculum*, and the sub-questions *how do teachers’ metastrategic and PCK change between the summer workshop and the reflection period following the implementation of the Project NANO unit and of the nine “big ideas” in nanoscale science and technology, which are the big ideas that teacher chose to teach in their Project NANO lesson and why?* From the categories, I interpreted themes that allowed for deeply contextualized descriptions of knowledge and skills teachers drew upon to respond to the challenge of integrating new information into curriculum.

**Data Analysis of Focus Groups.** Focus group and individual interview data were also coded and analyzed to examine evidence of teacher’s metastrategic thinking and PCK related to their inclusion of nanoscale concepts and technology into the curriculum. The audiotapes of the focus group and individual interviews were transcribed verbatim. For a list of transcriptions rules used for this study, please refer to Appendix O. I then analyzed the transcripts with NVivo by applying one or more codes to each section of text. Similar to the analysis of the CoRes and their associated call-outs, I determined sections using the strategies described above. I then used the software to identify codes
with similar meaning and reduced the number of codes by selecting the most salient code to describe the meaning of the utterance. Finally, I manually focused coded the transcripts data by clustering initial codes that described factors of teachers' thinking under categorical headings for metastrategic thinking, which were scope and sequence.

Next, I employed the same approach to establish categories and thematic patterns of teachers' PCK. I first clustered initial codes into categories and organized thematic patterns under each of these categories. Thematic patterns were determined by grouping together codes that related to similar ideas such as technical challenges and solutions as one thematic pattern and classroom organization themes as another. Next, I returned to the transcripts for each interview and the focus group to determine the context of the coded data and resulting thematic patterns to identify the form or forms of PCK the teacher referred to establish focused codes and assigning the form of PCK related to each set of thematic patterns under each category. Again, these forms of PCK are knowledge of the content, curriculum, instructional strategies, student thinking, and student assessment (Shulman, 1986; Magnusson et al., 1999).

With the intention of developing a more complex understanding of the interview data, I focus-coded the entire corpus of interview data and focus group data a second time, this time applying a more refined lens using two main frames that I chose based upon patterns developed in the first round of focused coding. First, I re-focus coded for how teachers thought about how to structure their units in terms of their rationales for establishing the scope and sequence of the unit within the course and second, I re-focus coded for how teachers drew upon their PCK to consider and describe some pedagogical
implications of various approaches to establishing developmentally appropriate scope and sequence for the nanoscale unit of instruction.

After completing the second round of focused coding, I color-coded with a unique color each of the categories with their sets of thematic patterns and their attendant forms of PCK. I then analyzed the thematic patterns by manually moving codes around on the page to identify relationships between the categories, factors of teachers' thinking and thematic patterns. Once again, I applied the concept mapping approach (Novak, 1990) to draw lines between the codes as another means to examine the relationships between codes. I noted these relationships as researcher memos. I compiled the resulting categories, factors of thinking and thematic patterns into two tables, a metastrategic thinking table and a PCK table. Finally, I visually scanned the color-coded transcripts and selected direct quotations to fit each of the researcher memos about relationships between participants’ ideas to exemplify teachers’ thinking for each of the inter-related categories, factors of teachers' thinking and thematic patterns.

The categories, factors of teachers' thinking and thematic patterns developed from the interview and focus group data were triangulated with the codes for the CoRes, call-out reflections and units of instruction scores to triple check that I had correctly interpreted each teacher’s meaning as best possible. The resulting data tables and narrative reported in Chapter Four informs the research question, How do teachers negotiate the inclusion of novel science content and novel technology into the curriculum and sub-questions How do teachers’ metastrategic and PCK change between the summer workshop and the reflection period following the implementation of the Project NANO
unit and Of the nine “big ideas” in nanoscale science and technology, which are the big ideas that teacher chose to teach in their Project NANO lesson and why?

Data Analysis of the Unit of Instruction. Here I describe the analysis of the units of instruction developed by the participants in the summer workshop. As mentioned in the data collection section, an important clarification is that several units of instruction were developed by teachers who worked in groups or pairs, some were generated by individual teachers. The groups and pairs of teachers developed and submitted one unit of instruction at the conclusion of the summer workshop rather than providing an individual unit plan for each person. However, in some cases, individual teachers revised their unit-plans in the months following the summer workshop and submitted the revised plan for analysis. One teacher submitted two units of instruction following the summer workshop – one unit of instruction for chemistry and one for biology.

I analyzed each unit of instruction submitted at the conclusion of the summer workshop and in the months following for the purposes of this study. The reason that I analyzed both of the units submitted by teachers is that this analysis provided the opportunity to compare the units to find examples of changes in teachers’ thinking, evidence that informs the sub question, how, if at all, do teachers’ metastrategic thinking and PCK change between the summer workshop and the reflection period following the implementation of the Project NANO unit?

To analyze the 21 units of instruction developed and submitted by groups and individual teachers, I used the locally-developed Knowledge, Skills and Experiences scoring guide (Becker, 2008). Although the instrument is not a validated instrument, the
scoring guide has been used for a variety of PD workshops since 2008 and continues to be refined and improved with each use (see Appendix L for the scoring guide).

Upon the conclusion of each of the summer workshops, I used the scoring guide to evaluate five different elements of the unit. These elements are: knowledge and concepts, science inquiry and engineering design skills, student experiences, learning community and assessment of student achievement. The scoring guide provides guidance to evaluate four or five aspects of each of those elements using a three-point scale. For example, the Knowledge and Concepts curriculum element requires the assignment of a 0, 1, 2, or 3 score in the following categories:

a. Appropriate grade level conceptual knowledge instruction is organized around a big idea in science,

b. Clear expectations are stated, in student language, about the science knowledge objectives for students,

c. Oregon science grade-level benchmarks/standards are explicitly embedded in the unit,

d. New conceptual knowledge is introduced with developmental links to prior learning.

(Becker, 2008, p. 2)

I followed the instructions provided on the cover page of the Knowledge, Skills and Experiences scoring guide (Becker, 2008) to score each of the curriculum elements. These directions read:

- Score a criterion statement with a “3” if the science activity/unit is exceptional and represents the best practice for learning science through inquiry.

- Score a criterion statement with a “2” if the science activity/unit contains, at a functional level, the best practice for learning science through inquiry.
• Score a criterion statement with a “1” if the science activity/unit provides an opportunity for the best practice to occur but it is not explicitly included in the activity/unit and could be added with appropriate modifications.

• Score the criterion statement with a “0” if there is not an opportunity to include the best practice in the activity/unit.

(Becker, 2008, p. 1)

I totaled the scores for each curriculum element and then totaled the scores for the entire unit. I then compared the disaggregated scores for each curriculum element across each of the 21 units of instruction submitted and wrote researcher memos to record the potential relationships between each of the teachers’ background knowledge, experience and the unit of instruction scores.

For the next layer of analysis, rather than limiting the analysis to considering frequencies of numerical scores assigned by applying the scoring guide, these scores were used to descriptively characterize the units by identifying whether or not teachers addressed each of the categories in the unit planning template and how each of the elements of the units themselves addressed each category of analysis in the scoring guide. I triangulated the pre and post survey rubric scores with the units of instruction and CoRe writings and considered each teacher’s entry point into the process of learning nanoscale science concepts and negotiating the inclusion of nanoscale science and research grade microscopes (SEM and Leica) into the curriculum in the context of Project NANO.

Next, I drew upon the unit plan, the CoRe and call-out reflections to inform the design of focus group questions that probed teachers’ thinking with the goal of encouraging them to communicate their metastrategic thinking used to select ideas from their PCK for incorporating nanoscale science and technology into the curriculum.
For example, analysis of the units of instruction indicated that a number of novice and veteran biology teachers and middle-level teachers in the three workshops drew upon their metastrategic thinking to establish the scope of their units of instruction to focus on concepts and processes related to biological evolution. From there, teachers drew upon their PCK to narrow the scope of their unit by choosing different developmentally appropriate learning objectives and selecting different big ideas in nanoscale science and technology to include in their units. By asking teachers during the interviews about these differences between the specific topics they chose to include in their set of learning objectives and different instructional strategies they employed in their unit and triangulating their responses with the CoRe and call-out reflections, I established that middle-level teachers focused more on the affordances of the SEM to examine morphological evidence of biological adaptations of organisms and high school teachers built upon students’ foundational knowledge of biological adaptations to use the SEM and Leica to teach about genetics and the morphological characteristics of species that may be attributed to interactions between genotypes and phenotypes.

**Data Analysis for the Classroom Observations.** Recall that I utilized the EQUIP classroom observation protocol (see Appendix N) to conduct observations in six of the 23 teachers’ classrooms. EQUIP includes the following features that supported the interpretation of each classroom observation. Table II in EQUIP is a form entitled *Time Usage Analysis.* Every 15 minutes, I referred to the code sheet and entered a code into each cell of the appropriate column. The columns are labeled “activity code,
organizational codes, student attention to lesson code, cognitive code, inquiry instructional component code, assessment code” (Marshall et al., 2009, p. 3).

The first column labeled activity code-facilitated by the teacher requires a score of zero for non-instructional time, one for pre-inquiry, two for developing inquiry, three for proficiency inquiry and a score of four for exemplary inquiry. The second column labeled organizational codes—led by teacher requires a code of W for whole class, S for small group and I for individual work. The third column labeled student attention to lesson code—displayed by students requires a code of L for low attention meaning 20% of fewer of the students are attending to the lesson, M for medium attention with between 20-80% of students attending the lesson or H for high attention with 80% or more of the students attending to the lesson. The fourth column labeled cognitive code-displayed by students requires the entry of a 0 for other (classroom disruptions, non-instructional portion of the activity and administrative activity), a one for receipt of knowledge, two for lower order thinking, three for apply, four for analyze/evaluate and five for create (combine, construct, develop and formulate). The fifth column labeled inquiry instructional component code-facilitated by teacher requires assignment of a zero of non-inquiry time, one for engage, two for explore, three for explain and extend. And finally, the sixth column labeled assessment code-facilitated by teacher requires an assignment of zero for no assessment observed, one for monitoring, two for formative assessment and three for summative assessment (Marshall et al., 2009).

Following each observation, I applied the scoring guide to tabulate the data entered into the Time Usage Analysis table to score instructional factors, discourse
factors, assessment factors, and curriculum factors on a four-point scale ranging from pre-inquiry (level 1) to exemplary inquiry (level 4), (Marshall et al., 2009). Each of the four factors (instructional, discourse, assessment and curriculum factors) has its own page in the scoring guide. The scores for each component was an integer from one to four that correspond with the appropriate level of inquiry. The final page in the protocol is a summative overview wherein I wrote brief descriptive comments to justify the individual factor scores and the comprehensive scores. These scores are intended to reflect the essence of the lesson relative to each component and are therefore not exact averages of all sub-scores in a category (Marshall et al., 2009).

Throughout each of the observation, I also took extensively fieldnotes, which were later used to provide context to the scores and the written summaries for each of the factor scores. The fieldnotes were also useful to inform closer inspection of particular instructional elements during subsequent observations and useful to inform the development of interview questions.

Data from the classroom observation scoring guide and researcher fieldnotes taken throughout each observation were triangulated with the rest of the Resource Folios data and the pre and post survey data to inform the research question, how do teacher participants in the 2012 Project Nanoscience and Nanotechnology Outreach (NANO) program negotiate the inclusion of novel science and novel technology into the science curriculum and the sub-question, how do teachers’ metastrategic and PCK change between the summer workshop and the reflection period following the implementation of the Project NANO unit?
Use of fieldnotes and workshop artifacts to provide context. I drew upon researcher fieldnotes taken during the three workshops, classroom observations and informal conversations with teachers before and after observations to provide contextual information developed from the CoRe and units of instruction data and possibly in comments made by participants in the focus group.

To be clear, I analyzed the CoRes and developed categories, factors of thinking and themes prior to comparing fieldnotes to the CoRe data to prevent biasing the CoRe coding process. The fieldnotes were used to provide background and description of situational data and were not analyzed separately.

For example, one of the key elements of the workshop is the calibration of language related to science, technology and pedagogy. Specifically, the protocol for preparing and adhering samples onto the metal, pin-shaped specimen mount called a *stub* and loading the stub into the SEM requires very specific language to ensure that the $900 sample cup is not damaged and that the microscope stage is not damaged, which can cost $7,000-$10,000 to repair. The workshop instructors provided a handout with this sample preparation and loading protocol and showed a short YouTube video demonstrating the protocol. Rather than pulling aside each teacher participant to do a formal performance-based assessment, the instructors decided to use a Vygotskian approach and observe each individual during lab time and to ask participants each time they approached the instruments to verbally describe the protocol as they loaded each sample. In this way, the workshop instructors were explicitly modeling exactly how they wanted teachers to have their own students learn and use the SEM sample preparation and loading protocol.
After I analyzed the CoRes and reviewed the classroom observation scores, I reviewed my fieldnotes to find evidence of how teachers used the scientific language employed in the summer workshop and to find instances where teachers deviated from procedural language used in the workshop, as well as evidence for why teachers chose to use alternative vernacular to describe procedures. I found that in nearly every case, teachers carefully maintained the formal procedural language used in the summer workshops and ensured that students did the same.

Data analysis of pre and post surveys. All 23 the participants’ pre and post surveys were scored with a locally developed rubric (see Appendix G). The workshop instructors and researcher scored a set of pre-service teachers’ pre and post surveys to improve the validity and reliability of the instrument (which is not to say that the survey is a validated instrument). Once inter-rater reliability was established, the researcher scored each of the teacher participant’s pre and post surveys. This process was repeated for the second set of pre and post workshop surveys since the instrument was changed between the first and second summer workshop in response to the inter-rater reliability discussions and comments from participants as to how to improve each item on the survey provided after they took the surveys.

For the purposes of reporting, only the survey scores of the 23 participants in this study were included in this dissertation research. The pre and post surveys for the first workshop were analyzed and reported separately from the pre and post survey used for the second and third workshop, due to the fact that the items on the survey changed between the first and second workshop.
Teachers’ scores were entered into a table with each row displaying the pre and post survey raw scores, as well as the mean, medium and standard deviation between each workshop groups’ scores. In the case of the multiple choice questions, the category of responses is dichotomous, indicating a correct or incorrect response. The categories of responses for the open-ended questions are based upon a three point scale; thus, there are four possible levels of responses with 0 representing either no response or a completely incorrect response and three representing a correct and complete response to the question according to the scoring guide criteria. I used the scoring guide to assign the appropriate score for each survey and then conducted a statistical analysis to establish the mean, medium and standard deviation for the multiple choice questions. I then disaggregated these data for each participant and each survey item. This detailed level of analysis provided quantitative data that indicated each participant's gains scores, a lack of gains for each survey item and in the case of three participants, demonstrated a ceiling effect resulting in no change between the pre and post survey scores on most of the survey items.

The result of this analysis provided data to the researcher, workshop instructors and readers of this research about what teachers learned and what misconceptions and gaps in knowledge were addressed or possibly persisted by the end of the workshop. This comparative analysis provided evidence to inform sub question that asks, *do teachers demonstrate scientific content knowledge gains in response to the 2012 Project NANO summer workshop?* However, the intended use for the data table is not simply numerical but also is descriptive, as well.
Here is an example of how analyses of the survey data were used in a design-based approach to improve Project NANO on an on-going basis. Analysis of the pre and post survey scores revealed that a number of teachers in the first section of the summer workshop were unclear about concepts to do with size and scale, a critical foundational construct in nanoscale science. Based on the high frequency of zero to one scores on question number one of the survey, *what is the difference between an optical microscope and a scanning electron microscope (SEM)*?, the instructors had evidence that they should add a lesson at the beginning of the second and third summer workshops related to size and scale. The intention of this instructional move was to support participants to be more successful in their personal scientific inquiry process during the workshop and to ensure that teachers embed accurate information related to how the SEM works in comparison to a light microscope in their units of instruction.

**Study Timeline**

The research took place during the 2012-2013 academic year drawing upon extant program evaluation data generated during the summer 2012 workshops and data generated during unit implementation cycle and within 5 months following the implementation of the instructional units (September 2012 through February 2013). Data analysis and drafting of dissertation, as appropriate, took place throughout this cycle. Figure 10 found on page 169 is a timeline of the study.

To summarize the timeline, keeping in mind this dissertation study is nested in the Project NANO program evaluation, evaluation data collection began in June of 2012 and
continued through July of 2013. However, data collection for the dissertation concluded at the end of February, 2013. As part of the program evaluation, the units of instruction and pre and post surveys were scored immediately at the beginning and ending of each summer workshop. Scoring and analysis of updated drafts of the units of instruction submitted by the teachers and the coding and analysis of the CoRe tables and call-out reflections began in October of 2012 and continued through February, 2013. The focus group and individual interviews were held in January and February, 2013. Focused analysis of the corpus of the Resource Folios data and the penultimate write up of the dissertation was completed by May 30, 2013, at which point the dissertation was submitted to the dissertation committee for review two-weeks prior to the defense. The successful dissertation defense occurred on June 13, 2013 and changes recommended or required by the committee occurred throughout the months of June and July. The final dissertation was electronically submitted by the Office of Graduate Studies deadline of July 26, 2013.
Figure 10. Dissertation timeline
Research Integrity

In this section I address several aspects regarding research integrity: confidentiality for participants, informed consent and safety of those participants, as well as my role as the internal evaluator and dissertation researcher, including benefits and drawbacks of being in both roles at once and strategies I employed to negotiate this tension. Finally, I describe three limitations to this study.

Participant Confidentiality. I begin with addressing the confidentiality of the participants. No actual names of teachers or students have been used in the dissertation study or will be used in any subsequent publications. I created a codebook of pseudonyms for each of the teachers who participated in the project. In accordance with school district and university Human Subjects Research requirements, this codebook will only be made available to the people included in the approved IRBs, the Principal Investigator on the project, the two co-principal investigators who are also the workshop instructors/coaches, my dissertation chair/advisor and me.

The reason that this codebook will be available to the Principal Investigator and co-instructor/coaches in addition to myself and my dissertation advisor is that some of the teacher participants were involved in a summer follow-up workshop designed to address specific issues teachers encountered throughout their experience in the first year of this design-based program. Knowing the real identity of the participants helped the coaches/instructors discuss the needs of each participant and target support as needed during the workshops and follow-up coaching sessions. Furthermore, Project NANO is designed to encourage teachers to participate in the program over a 3-year period; thus,
the data and analysis conducted in the evaluation and dissertation study will be helpful to the collaborative process to tailor the workshop and one-on-one coaching to the specific needs of the participants who chose to continue in the program over the next two years.

Each of the teacher participants in the study was fully informed about the study at the beginning of each workshop immediately after taking the pre survey and those who agreed to participate signed an active informed consent form and a Project NANO Memorandum of Understanding. Teacher participants also signed a release form to allow the inclusion of photo micrographs they created in the workshop in the dissertation or any subsequent publication. Study participants were encouraged to share the informed consent form and/or the Memorandum of Understanding with their building principal, other teachers in their schools and anyone else whom they felt might be impacted by their participation in the study. Both the university’s IRB informed consent form and the photo release form were included in the Human Subjects proposal that was conditionally approved in November 2011 prior to the summer workshops and was later granted full approval.

In addition, students in each teacher’s classes were provided with informed consent forms; some districts required passive and other required active consent. No pictures of students were taken, although the student informed consent does provide the researcher with permission to publish photo micrographs students captured with either the SEM or Leica to be published in the dissertation and subsequent publications. In accordance to institutional review board (IRB) requirements, students’ names, the
teacher’s names or the name of their school or school district will not be ascribed to these images, although their grade level is and will be noted in this and future publications.

This research received conditional approval on November 18, 2011, and final approval March 28, 2013, from my university's Human Subjects Research Review Committee. Furthermore, this research received formal written approval from each of the school districts and the private school Human Subjects review board or IRB officer as appropriate. Each of the human subjects proposals received IRB approval for a three-year period, the duration of the 2012 Project NANO cohort's expected involvement in the program.

Next, I describe potential risks and safeguard for the participants in this study. The main risks involved in this study were a sense of embarrassment, confusion or frustration on the part of the teacher participants who were working to learn how to use SEM while at the same time endeavoring to design and implement a new unit of instruction for the first time while they were being observed through the program evaluation and research. In recognition of the fact that there may have been a steep implementation dip (Fullan, 2011) as teachers learned to negotiate novel science content and technology and teach a new unit, three measures were designed to reduce anxiety on the part of the participants.

First, the researcher served as a participant-observer in the three summer workshops. The researcher and instructors each shared stories of their own experiences including their personal struggles and that of their students to learn about the nanoscale and the scanning electron microscope and how to use the instrument. Throughout the
open-laboratory activities, the researcher participated in conversations about how to use the SEM and the optical microscope with students, thus building a sense of trust and shared feelings of excitement about the experience of venturing into the unknown as co-instigators. The researcher also repeatedly said both orally and in writing that the purpose of the program evaluation and dissertation research was to describe teachers’ metastrategic thinking and PCK to inform the improvement of teacher PD programming and that the purpose was not to judge or evaluate teachers’ proficiency in developing and implementing a nanoscale unit of instruction.

A second measure involved the researcher meeting separately with the teachers who expressed an interest in participating in the study at the beginning of each of the summer workshops. Doing so encouraged a clear sense of what was involved in the research and the evaluation and explained the role of the participants in the both studies. I also established the preferred means for communication for each study participant. Each group met for 45-minutes to answer questions, discuss any concerns and ensure that every participant fully understood the research questions, the methods, the timeline and the data that teachers would be asked to share as part of the study. In addition to the active informed consent form, the teachers each signed a memorandum of understanding (MOU) indicating that they clearly understood the elements of the research and their role in the study and that they agreed to participate in all aspect of the evaluation and research. Both the MOU and active informed consent forms indicated that teachers might withdraw from the study and evaluation at any point and that doing so would in no way affect their relationship with the Project NANO team, the university, their school or
district or the other teacher participants in the program. Blank MOU and informed consent forms are posted to the Project NANO Wiki website.

Two weeks before each teacher was to teach his or her Project NANO lesson, the appropriate coach and the researcher contacted each teacher to review the goals and methods of the research and to clarify any questions teachers might have had about the data requests. Within one or two days of the end of the unit of instruction, the researcher contacted each teacher to make sure that each teacher understood the data requests and to discuss how the teacher wished to deliver that data. In some cases, teachers felt more comfortable having the researcher personally come to their classroom to collect their written CoRe call-outs and conduct one-on-one interviews with them and in other cases, teachers felt more comfortable mailing the data electronically or through the U.S. mail and then participating in a focus group at the university. The researcher made every effort to ensure the comfort of each teacher participant by accommodating each request.

A third measure put into place to minimize emotional stress on the part of the teachers was to divide up the group of teacher participants into two groups after the summer workshop. Groups of teachers were assigned based on the geographical proximity of the teachers’ schools to that of their coach; each group of teachers had a coach assigned to them whom they contacted to discuss anything having to do with Project NANO, including the research. Recall that the teachers already knew the coaches because these were the same veteran teachers who served as the summer workshop co-instructors. Our intention was to facilitate a situation wherein the coach and the set of teachers with whom he was working developed a sense of trust and feeling that if they
needed to talk with someone other than the researcher about the research, teachers had someone they knew that they could talk with about their ideas. Our thought was that this situation created a safety buffer for the teachers to confidentially share their concerns with their coach rather than having to directly reveal their identity to the researcher. Alternatively, teachers were also provided the name and contact information for the Project NANO Principle Investigator and the university IRB chair in case they needed to speak with someone whom they viewed as being more removed from their situation. None of the participants chose to contact either the program Principle Investigator or IRB chair with any concerns.

**Strategies used to negotiate dual roles.** Here I describe the strategies that I used to negotiate my role as both the internal program evaluator and dissertation researcher. All of the data collected for the dissertation was drawn directly from the data sets collected for the evaluation. There are no data sets that are unique to the dissertation that are not found in the evaluation. There are, however, additional sets of data that were collected for the evaluation that were not examined for the dissertation study. The reason for this difference is that the goals and research questions of the internal program evaluation differ from that of the dissertation study, especially because the program funder has asked for student learning outcome data to be included in the evaluation. The dissertation study focused on teacher thinking and, therefore, the data set included in the dissertation study is restricted to a sub-set of the evaluation data that directly relates only to teacher thinking.
For example, the evaluation study incorporated student work samples that will be scored using the state of Oregon Science Work Sample Scoring Guide. The evaluation also tracked the number of students who drew on nanoscale science and nanoscale technology for a science fair project and the number of students who go on to major in a STEM discipline in college. These data fell outside of the scope of this dissertation study.

Potential issues may have arisen because I conducted a limited number of observations ($N = 7$) and I scored a small number of work samples by the end of December. I collected the last of the data for the dissertation study in February of 2013. Throughout the development of the dissertation study, I needed to remain clear in my own mind about the difference between the evaluation and dissertation study to avoid making generalizations about teachers’ thinking based on the student work samples. To do this, I recorded my thoughts while I scored the work samples. This way any thoughts that I had as a result of analyzing student work samples was captured and I was able to refer to these notes during the analysis of the dissertation data to check for preconceived ideas that may have influenced the assignment and sorting of codes. I generated a list of any preconceived ideas that I had based on the evaluation data, my intuition and personal experiences and kept it next to me while I coded the CoRe, call-out reflections and interview transcripts to ensure that the code(s) assigned to each section authentically came from the teachers’ words and ideas, not from my own ideas about what participants’ may have meant in a broader sense.

Another strategy used throughout the study was that I met on a regular basis with the Project NANO team. I met with the team once or twice a month during the 2011-2012
academic year as I designed both the evaluation plan and the dissertation plan and then we met again in September of 2012 for a full-day meeting to discuss both the plans for the evaluation and for the dissertation research to make clear distinctions in all of our minds the difference between the two efforts. This meeting included clarifying the different questions, methods, analytical strategies and products that would be generated as a result of each effort.

Overall, I firmly believe that my dual role as both an evaluator and a dissertation researcher has been beneficial to both efforts. Again, my intention has been to generate an evaluation report and a dissertation that informs the improvement of Project NANO and contribute a set of Resource Folios that will be made available to pre-service teachers, novice teachers and teachers working to figure out how to negotiate the inclusion of nanoscale science and technology into the curriculum they used.

**Trustworthiness and credibility.** As a member of the Project NANO team over the past 3 years, the project has benefited from my expertise contributing to the design of the project–for example, choosing to embed the Wiggins and McTighe (2006) backwards design process, the 5E Instructional Model (Bybee, 1997), Resource Folios approach (Loughran et al., 2006) to planning the unit, and teaching specific scientific-inquiry based learning pedagogical strategies. I also brought to the team new ways to think about the evolution of the coaching model that emerged from the collaboration between a university-level disciplinary scientist and two veteran teachers. This experience meant that I was aware of the rationale behind the program design including the learning theories and how they are applied, the learning outcome goals for the program itself and
the evolution of the strategies as we have drawn upon our own metastrategic thinking and built upon our own PCK using a design-based research approach.

The creation of the dissertation questions contributed greatly to refining the focus of my observations for the program evaluation during the summer workshops and helped to attune my attention to instances where teachers shared their metastrategic thinking and drew upon their PCK to negotiate how they would design and refine their units of instruction. The process of designing the dissertation study also attuned my attention to the markers teachers said that they would put into place to assess the degree of success of specific classroom strategies and their plans for how to adapt lessons in the event that students were less than successful during particular activities. The iterative process of gathering and analyzing data for both the evaluation and the dissertation study has informed each effort and refined my own ability to essentially allow the data to speak for itself.

For example, one of the exercises in which the Project NANO team and I have participated is to work to establish reliability and validity of our locally developed instruments. Recall that over the year prior to the summer workshop, I met on a regular basis with the two workshop instructors/coaches to refine the scoring guide and rubric used for the summer workshop. Following the first summer workshop, the three of us scored a set of pre-service and elementary teacher participant surveys to establish inter-rater reliability on the rubric and to fine-tune the instrument. In the second workshop, we collaborated to do the same thing with the revised rubric and found a high level of inter-rater reliability on the rubric. Following the third summer workshop, the team also
applied the scoring guide to the units of instruction and refined this instrument as well by 
scoring a set of elementary and pre-service artifacts that are not part of the study set.

As mentioned elsewhere, a set of additional questions was added to the CoRe 
template developed by Loughran et al.’s (2006) group. These questions were developed 
by the Project NANO team including the researcher. Three pre-service teachers then 
practiced using this pre-unit planning strategy by filling out several CoRe tables just as 
the teachers would do to test the clarity and usefulness of the additional questions. 
Several teachers in the summer workshops reported that the questions on the CoRe were 
clear and helpful in the process of pre-thinking the unit they were about to design.

In addition to the work to improve the reliability and validity of the instruments, I 
am also deeply grateful for a very honest Project NANO team, dissertation cohort and 
advisors who did a great job at pointing out assumptions I may have been holding when I 
discussed the questions and the data as it came in. Their questions and discussions pushed 
me to dig deeper to find the authentic story from the teacher participants’ perspective.

**Limitations of this Study**

First, by examining teachers’ PCK in the way I designed this study, there are 
aspects of teachers’ thinking that I did not approach. For example, by applying a 
framework that examines teachers’ metastrategic thinking to access teachers’ PCK, I did 
not examine or attempt to characterize teachers’ entire cognitive process or even their 
extire metacognitive process. Second, although there are researchers (e.g., Veal & 
MaKinster, 2010) who include external social pressures in their definition of PCK, I 
chose not to do so and, therefore, I limited the examination of teachers’ PCK to consider
only topic-specific PCK as it relates to how they negotiated the integration of novel science content and technology in the curriculum to facilitate the development of students’ higher order thinking skills. A third limitation is that even though there were elementary teachers and pre-service teachers in each of the summer workshops, I focused on examining only the secondary level teachers’ metastrategic thinking and PCK. Admittedly, this choice to restrict the dissertation study to practicing secondary teachers’ thinking may potentially oversimplify the portrait of PCK depicted, but this decision allowed for the creation of a thick and rich descriptive case study that will inform the design of later studies that will include parameters not addressed in this foundational study.

Summary

In Chapter Three, I have presented the research design and methods of this design-based, descriptive, multi-case study. The research methodology drew heavily on an approach called Resource Folios developed by Australian researchers Loughran et al. (2006) and used in earlier studies conducted by the Loughran research group. This multiple descriptive case study entailed two levels: a group of 23 teacher participants and a subset of 14 teachers who implemented their units in the fall and winter of 2012 and 2013. The Resource Folio data collected for the entire group involved (a) the CoRe table developed by teachers in preparation for planning their two-week unit of instruction incorporating nanoscale science and technology into the curriculum; (b) the PaP-eRs, a collection of artifacts which were the pre and post content workshop survey data, and units of instruction developed by the teachers; and (c) researcher fieldnotes. Additional
data collected for the sub-group was a focus group, four individual interviews and reflective call-outs reflections.

The analyses and triangulation of data from these sources provided a description of secondary teachers thinking from a variety of perspectives. For instance, by comparing data collected at the beginning of the summer workshops with data generated during the implementation of the units of instruction and following the implementation of the unit, the study described teachers’ rationales for the choices they made and changes in their thinking throughout the unit implementation and reflection cycle.

**Contribution of this study to the field of science education.** The potential contributions that this study can make to the field of science education are two-fold. The dissertation research itself will add to a small but growing body of literature that examines topic-specific examples of how teachers negotiate the inclusion of novel science content and novel technology into the curriculum, specifically nanoscale science and technology. Whereas the Loughran research groups’ (personal communication, April 29, 2013) Resource Folios PD and research projects to date focus on the most common topics and problems of practice encountered by all science teachers, this study builds upon the work of the Loughran group by providing an example of how to access teachers’ thinking about the process of navigating novel science and novel technology. Given the pressures that teachers are currently experiencing to rapidly integrate novel technology and concepts into their already packed curriculum, I believe that the expansion of the Resource Folios approach to eliciting and capturing teachers’ PCK related to not-so-common, but rapidly emerging problems of practice is a promising
development in the application of Resource Folios as a value-added research methodology.

In addition to the dissertation itself, the final product of this study is a compendium of four teachers’ Resource Folios (see Appendix items A through D). The purpose of this compendium of four Resource Folios is to aid new teachers, teachers teaching out of their content area and teachers who seek assistance to integrate nanoscale science and technology into the classroom curriculum. Research findings will also inform the continuous improvement of Project NANO and the establishment of an evaluation protocol for the program going forward. This protocol may prove useful to other programs seeking tools for their evaluation.

The collection was selected based upon the topics in science that they address. Three of the Resource Folios were selected because they exemplify teacher’s thinking about how to teach topics that are frequently addressed in units developed by members of the 2012 cohort. In one case, I selected a teacher’s Resource Folio because his work exemplifies his thinking about how to teach big ideas in nanoscale science that have not been well addressed in the literature to date.

For example, Stevens et al. (2009) pointed out that most teachers involved in their research were approaching the inclusion of nanoscale concepts by teaching topics related to size and scale, structure of matter and size dependent properties. Few teachers were approaching ideas related to forces and interaction or tools and instrumentation; therefore sharing the Resource Folios of chemistry and physics teachers who address these topics
in their Project NANO units will make a significant contribution to the field by
addressing a current gap in the literature.

Finally, this dissertation research and its accompanying compendium of Resource
Folios may be of use to teacher professional development providers, pre-service teacher
educators, curriculum developers and anyone interested in learning more about how this
group of teachers working on the leading edge of science instruction applied their
knowledge, skills and experience to negotiate the challenge of integrating nanoscale
concepts and technology into modern secondary level science curriculum. This is a
challenge that all K-12 science teachers must be prepared to meet with the introduction of
the Next Generation Science Standards (Achieve, 2013).
CHAPTER FOUR

TEACHERS’ METASTRATEGIC THINKING AND PCK USED TO NEGOTIATE THE INCLUSION OF NANOSCALE SCIENCE AND TECHNOLOGY INTO THE CURRICULUM

Introduction

The purposes of this design-based descriptive case study were to examine teachers’ thinking to support teacher participants’ reflective practice, to inform the improvement of Project NANO, and to inform others working to integrate novel science and technology into secondary level science curriculum and teacher professional development. In Chapter Four, I present the results of this study, as a description of teachers’ thinking in Project NANO, specifically their metastrategic thinking and the pedagogical content knowledge the participating teachers drew upon to negotiate the inclusion of novel science and technology, specifically nanoscale science and technology, into the secondary level curriculum.

It is important to note that this research examined teachers’ thinking within the context of a teacher PD program that used a Resource Folio approach. Here, the Resource Folio approach was intended to engage teachers in a collaborative planning and reflective process by placing at the center of the process what teachers know and come to understand about how students learn specific scientific topics using higher order thinking skills and technology. Given the context of the Project NANO teacher PD program, planning included ideas related to affordances and limitations of technology as well as how technology may be used to facilitate the development of students’ higher order thinking skills as learners exploring concepts and processes in the natural and built world.
The chapter presents layers of description beginning with a depiction of the metastrategic thinking of the entire group of 23 teachers. The second section provides a detailed description of the forms of PCK the entire group of teachers used and built upon throughout the implementation cycle. The third section provides a closer look at the thinking of a sub-group of 14 teachers who completed the entire implementation and reflection cycle by the end of the data collection period in February of 2013. The chapter concludes with a summary of how teachers drew upon metastrategic thinking and forms of PCK to inform the research question *how do teacher participants in the 2012 Project Nanoscience and Nanotechnology Outreach (NANO) program negotiate the inclusion of novel science and novel technology into the science curriculum?*

Recall from Chapter Three that Resource Folios is a method designed by researchers at Monash University in Australia to support and examine the development of teachers’ pedagogical content knowledge. This method not only provided data for analysis, but also supported the reflective process of unit planning and implementation. Resource Folios are comprised of a CoRe table and PaP-eRs. Teachers in the Project NANO summer workshop worked in small groups or pairs to discuss questions posed in the CoRe table and then share their thinking by writing in each cell of the table. Examples of the questions included “Why is this topic important for students to learn?” and “What are some common barriers or limitations for students learning this topic?” This collaborative experience provided teachers with the opportunity to thoughtfully choose and communicate a set of science learning objectives into frame their units of instruction around and then to consider what they knew about the science content,
curriculum, and student thinking related to those learning objectives prior to planning a two to three week nanoscale science or engineering unit of instruction.

Throughout the implementation cycle of their units, teachers were asked to add reflective comments known as call-outs (Loughran et al., 2006) directly on the CoRe table they created in the summer. Thus teachers’ call-out reflections were in response to their own prior thinking and that of their group or pair who co-planned the unit of instruction. Teachers’ call-out reflections, units of instruction, pre and post workshop surveys, classroom observations, focus group and individual interviews comprise the PaP-eRs portion of the Resource Folios. Fieldnotes and workshop artifacts completed the data sources.

A variety of analytical tools were applied to examine the research data. The CoRe table, call-out reflections and interview transcripts were first open-coded using NVivo software. Next, I manually grouped codes into categories and then assembled themes from the data under each of those categories. In the case of PCK, each of the themes was characterized as evidence of one or more of the five forms of PCK to be discussed later.

A locally developed scoring guide entitled Knowledge, Skills, Experience, Learning Communities and Assessment was applied to analyze units of instruction developed during the summer workshop. In some cases, teachers radically revised their units of instruction prior to teaching the unit and requested that the researcher include the revised unit in the research as a more authentic depiction of their thinking. The pre and post surveys administered on the first and last day of each of the three summer workshops were scored using a rubric developed by the researcher with the summer
workshop instructors and analyzed for patterns of responses useful to inform the content and format of the summer workshops, the follow-up coaching support and the dissertation research. And finally, four sets of classroom observations were conducted in a sub-sample of classrooms using the Electronic Quality of Inquiry Protocol (EQUIP), (Marshall et al., 2009) and extensive fieldnotes. The purpose of the EQUIP was to characterize lessons on an inquiry continuum ranging from developing inquiry which is highly teacher directed to exemplary inquiry which is student-centered, open-ended inquiry.

In order to raise up and describe the study’s results, such as factors contributing to and thematic patterns of teachers' thinking, Chapter Four is organized around key elements of, first, their metastrategic thinking and, then, their PCK, followed by results related to changes in the teachers’ thinking. As mentioned near the end of Chapter Three, four complete Resource Folios are presented in Appendices A through D for two middle-level and two high school teacher participants as a contribution to the readers’ more complete understanding of how the data from each instrument was analyzed and interpreted; just as importantly, each Resource Folio serves as a discrete example of a particular teacher’s thinking.

**Teachers' Metastrategic Thinking**

Recall that in Chapter One the term metastrategic knowledge was defined by Zohar (1999, 2006) as a sub-component of teachers’ metacognition that is explicit knowledge of the cognitive procedures used by the teacher to facilitate students’ understanding of how to approach learning specific topics:
It consists of the following abilities: making generalizations and drawing rules regarding a thinking strategy; explaining when, why and how such a thinking strategy should be used, when it should not be used, what the disadvantages are of not using appropriate strategies, and what task characteristics call for the use of the strategy. (Zohar, 2006, p. 337)

As a researcher, I was inspired by Zohar’s ideas about metastrategic knowledge to think about the application of this knowledge. I believe that knowledge is something one has, thinking is something that one does. Thus, I drew upon the construct of metastrategic knowledge and reframed the construct in an active sense to consider metastrategic thinking. Although metastrategic thinking may refer to the teachers’ and the learners’ cognitive processes, this study is specifically focused on examining and describing teachers’ metastrategic thinking that informs their teaching strategies in nanoscale science and technology.

Throughout the process of planning the units of instruction, during the Project NANO workshop, as well as during revisions that occurred just before and during the implementation of their implementation, teachers were explicitly guided throughout the summer workshop to plan units to involve high order thinking strategies. Examples for how to facilitate the development of students’ higher order thinking was embedded in several workshop presentations modeled by the instructors at the instruments and explicitly addressed during opportune moments when either a teacher or instructor would pause to discuss how an activity could be changed to progressively move students thinking from lower to higher order thinking. Throughout the process of planning the units of instruction, teachers applied their metastrategic thinking and PCK to analyze the potential of each approach to facilitate the development of higher order thinking skills in
students. Although many other selection criteria certainly informed teachers’ choices of instructional methods, when considering metastrategic thinking, it is important that the reader keep in mind that metastrategic thinking contributes to the development of a rationale supporting the choice of instructional methods to facilitate the development of higher order thinking skills among learners and thinking that informs other teaching and learning goals. As a researcher, the methods I chose were specifically selected because I was interested in examining and describing this group of teachers’ metastrategic thinking about how to facilitate higher order thinking and their PCK that informed their instructional choices.

Here, teachers in Project NANO discussed and considered a range of possible instructional choices, compared those choices, developed a set of reasons for choosing certain methods over others based on their potential to support higher order thinking and rejected other choices because they did not fit this key instructional goal. Experienced teachers brought more ideas to this decision making process because their very active imaginations had more PCK to draw from as they developed reasons to select from a range of instructional choices. Novice teachers had different entry-points into this process; however, they also applied their metastrategic thinking in much the same way to develop a rationale for their choices for how to structure their units. Regardless of what the entry points were for each teacher, depending on his or her background knowledge, skills, experiences and orientation to teaching science, all of the teachers applied metastrategic thinking to negotiate the inclusion of novel science and novel technology into the secondary science curriculum.
For example, during the summer workshop teachers debated whether or not students should have a laboratory experience to generally explore concepts before they received instruction on specific topics in the form of readings and a lecture. Some teachers expressed that it is important for students to know what they are looking for when they examine a sample so that they understand how to look and why they are looking. Other teachers thought pre-teaching concepts might restrict a students’ creativity and ability to look at samples from multiple perspectives before being narrowed down to consider a specific feature or set of characteristics. Interestingly, these conversations mirrored many of the conversations currently taking place regarding the implementation of the Common Core State Standards (2010).

Final decisions about which approach to take were based on discussions to do with the nature of higher order thinking and which instructional choices were likely to facilitate higher order thinking in their students. Teachers approached this question of higher order thinking, particularly the matter of the ongoing coordination of theory and evidence, from either a Bloom’s Taxonomy perspective or a nature of scientific thinking perspective. Some teachers couched this discussion in terms of using Bloom’s (Anderson & Krathwohl, 2001) taxonomy by gathering knowledge, comprehending and confirming and understanding being lower order thinking skills and applying, analyzing, synthesizing and evaluating all being high order thinking skills to analyze and compare instructional strategies (Pohl, 2006). Other teachers thought about high order thinking skills in terms of the distinction between scientific thinking and scientific knowledge in comparison to choices that develop students’ capacity for scientific thinking.
In the case of scientific thinking, teachers talked about the distinction between thinking *with* theories verses thinking *about* theories. These teachers emphasized that they wanted to create learning opportunities that they characterized as operating on the level of higher order thinking because students intentionally seek knowledge by coordinating theory and evidence. Thus students would apply critical thinking and problem solving strategies to think with and about theories throughout the learning process as they examine evidence and reflect on whether the evidence was congruent or discrepant with scientific theories.

Teachers considered this process of thinking with and about theories and evidence as an integral aspect of *doing science* at every step of the process, not an isolated event within the learning cycle. This is not to say that teachers considered as unimportant instructional strategies such as front-loading knowledge and providing opportunities for students to reflect on new knowledge and how concepts interrelate. Instead, teachers applied a filter to consider whether or not each of these strategies would function in service of supporting students’ abilities to coordinate theory and evidence. This filter was applied to ensure that theory revision becomes something that students do, rather than something that simply happens because someone told them to revise or because it happened outside of conscious awareness.

Regardless of whether the teachers approached this question of higher order thinking from a Bloom’s taxonomy perspective (Anderson & Krathwohl, 2001) or a nature of scientific thinking perspective, teachers communicated that what remained in the center was one key consideration. They said that when they considered one choice of
instructional methods over others, a key decision making criteria they discussed was the question of how explicit and intentional the instructional strategy would be in terms of facilitating students to think scientifically to coordinate theory and evidence.

I now turn to more specific results related to the teachers’ metastrategic thinking. Table 3 presents an overview of findings concerning the teacher participants’ metastrategic thinking that informed the development of their rationales as they negotiated the inclusion of nanoscale science and technology into the curriculum at the secondary level. I begin with a brief description of how the data are presented in the table.

The left column (scope and sequence) represents the areas of teachers’ thinking in which they developed their rationales for the structure of the unit. (Below, I describe findings related to the scope of the teachers’ units.) Relative to the scope of the unit, the right column names three sets of factors that contributed to the teachers' rationales for the scope of their units (affordances and limitations of scientific tools, state science content standards, and the field of science, technology, and society. The sequence of the unit refers to its chronological pedagogical placement within the science overall science course. Concerning the sequence, teachers considered three sets of different factors (the type of unit, limiting conditions, and factors that carry both affordances and limitations. Data presented in Table 3 inform the sub-question of the nine ‘big ideas’ in nanoscale science and technology, which are the big ideas that teachers’ choose to teach in their Project NANO unit and why?
### Table 3

**Teachers’ Metastrategic Thinking**

<table>
<thead>
<tr>
<th>Planning the Unit of Instruction</th>
<th>Factors of Thinking</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scope of unit</strong></td>
<td><strong>Affordances and Limitations of Scientific Tools</strong></td>
</tr>
<tr>
<td>o Science inquiry process</td>
<td>o Science inquiry process</td>
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<tr>
<td>o Complementary technology</td>
<td>o Complementary technology</td>
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<tr>
<td>o Student engagement</td>
<td>o Student engagement</td>
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<tr>
<td>o Debunking student misconceptions</td>
<td>o Debunking student misconceptions</td>
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<tr>
<td>o Consideration of students’ learning styles</td>
<td>o Consideration of students’ learning styles</td>
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<tr>
<td>o Emphasis on the constructs of size and scale and structure of matter</td>
<td>o Emphasis on the constructs of size and scale and structure of matter</td>
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<tr>
<td><strong>The Influence of State Science Content Standards</strong></td>
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<tr>
<td>o Established learning objective, big ideas in nanoscale science and selected appropriate state standards</td>
<td>o Established learning objective, big ideas in nanoscale science and selected appropriate state standards</td>
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<tr>
<td><strong>Science, Technology, and Society</strong></td>
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<td>o Bioethics</td>
<td>o Bioethics</td>
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<tr>
<td>o Potential dangers of nanoparticles</td>
<td>o Potential dangers of nanoparticles</td>
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<td>o Human health</td>
<td>o Human health</td>
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<tr>
<td>o Environmental health</td>
<td>o Environmental health</td>
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<tr>
<td><strong>Sequence of unit within the science course</strong></td>
<td><strong>Type of Unit</strong></td>
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<td>o End of a unit</td>
<td>o End of a unit</td>
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<td>o Extension unit used to reinforce ideas</td>
<td>o Extension unit used to reinforce ideas</td>
</tr>
<tr>
<td>o Conceptual bridge between units</td>
<td>o Conceptual bridge between units</td>
</tr>
<tr>
<td>o Out-of-sequence unit</td>
<td>o Out-of-sequence unit</td>
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<tr>
<td>o Influence of the time of year on choice of topics</td>
<td>o Influence of the time of year on choice of topics</td>
</tr>
<tr>
<td>o Consideration of instructional techniques</td>
<td>o Consideration of instructional techniques</td>
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<tr>
<td><strong>Limiting conditions</strong></td>
<td><strong>Factors That Involve Both Affordances and Limitations</strong></td>
</tr>
<tr>
<td>o The SEM</td>
<td>o Station rotations</td>
</tr>
<tr>
<td>o Students’ development</td>
<td>o Drawing on sample units for activities and ideas</td>
</tr>
<tr>
<td>o Increased class sizes</td>
<td>o Consistent use of language provided in the workshops</td>
</tr>
<tr>
<td>o Time</td>
<td>o Teacher gauging appropriate levels of cognitive demand</td>
</tr>
</tbody>
</table>
The Project NANO summer workshops provided participants with a conceptual, organizational framework described in an NSTA publication entitled *The Big Ideas of Nanoscale Science and Engineering; A Guidebook for Secondary Teachers* (2009). Participants were asked to begin planning by working with their lab group to choose five to eight topical learning objects including one or more of the big ideas in nanoscale science and technology to frame their units of instruction. From there, groups tested specimens to find out how well they imaged with the SEM, refined guiding questions for their inquiries and identified sub-learning goals for the unit. They used the backwards-by-design approach (Wiggins & McTighe, 2006) to select instructional methods to discuss and the pros and cons of various strategies so as to develop a set of rationale for each instructional choice. Key to these discussions was consideration for how to scaffold learning experiences that they believed would best support the development of student comprehension of interconnected scientific concepts and the development of laboratory skills using higher order thinking such as critical thinking and problem solving.

Although teacher collaborated to create their units of instruction, Table 4 tabulates which of the big ideas *each* of the 23 teachers included in their unit of instruction. In one case, a teacher chose to teach a Project NANO unit in both her chemistry and her biology course, so the big ideas included in each of her two units were counted separately. The data sources that informed these findings are the units of instruction and CoRe tables generated by the participants.
Table 4

*Number of Instructional Units that Included the Big Ideas in Nanoscale Science*

<table>
<thead>
<tr>
<th>Size &amp; Scale</th>
<th>Structure of Matter</th>
<th>Tools &amp; Instrumentation</th>
<th>Science, Technology &amp; Forces &amp; Interaction</th>
<th>Size-Dependent Properties</th>
<th>Models &amp; Simulations</th>
<th>Quantum Effects</th>
<th>Self-Assembly</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>24</td>
<td>24</td>
<td>14</td>
<td>13</td>
<td>9</td>
<td>9</td>
<td>3</td>
</tr>
</tbody>
</table>

Given that involvement in Project NANO means that teachers have the opportunity to borrow the SEM and Leica for use in their classroom, the big idea in nanoscale science *tools and instrumentation* would seem to have heavily influenced teachers’ thinking about the scope of their units of instruction. Perhaps because of the strong emphasis on the SEM and Leica in the workshops, teachers rationalized the inclusion of tools and instruments as well as the big ideas of size and scale and the structure of matter in their units more than any other big ideas in nanoscale science. Here I present teachers’ metastrategic thinking next to the scope of the unit category beginning with factors that fall under the big ideas of *tools and instruments* (see Table 5). For ease of understanding, I will reproduce a section of each table in each of the subsections with first the metastrategic thinking section and then the PCK subsection of Chapter Four.

I now discuss the three sets of factors relative to the scope of the teachers’ units in the order I do because teachers’ reported considering these sets of factors generally being
weighted in this order. Initially, teachers turned to the affordances and limitations of the scientific instruments.

**Affordances and limitations of scientific tools.** When building a rationale for the scope of a unit that would develop students’ higher order thinking skills, it is not surprising that teachers focused on the scientific tools they were provided through Project NANO. They especially concentrated on science inquiry process, but also on complementary technology, student engagement, debunking student misconceptions, students’ learning styles, and put emphasis on the constructs of size and scale and structure of matter. In the Table 5, I reproduced a section from Table 3 that centers on the findings concerning teachers’ metastrategic thinking in relation to the scope of the unit as a way to introduce this factor of teachers’ thinking:

**Table 5**

*Teachers’ Metastrategic Thinking; Affordances and Limitations of Scientific Tools*

<table>
<thead>
<tr>
<th>Planning the Unit</th>
<th>Factors of Thinking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scope of Unit</td>
<td>Affordances and Limitations of Scientific Tools</td>
</tr>
<tr>
<td></td>
<td>o Science inquiry process</td>
</tr>
<tr>
<td></td>
<td>o Complementary technology</td>
</tr>
<tr>
<td></td>
<td>o Student engagement</td>
</tr>
<tr>
<td></td>
<td>o Debunking student misconceptions</td>
</tr>
<tr>
<td></td>
<td>o Consideration of students’ learning styles</td>
</tr>
<tr>
<td></td>
<td>o Emphasis on the constructs of size and scale and structure of matter</td>
</tr>
</tbody>
</table>

The data sources for these findings were the instructional units and CoRe tables teachers developed during the summer workshop, interviews and classroom observations.
All of the units of instruction included a lecture and set of readings about how the SEM and Leica each work, the differences between the two types of microscopes and how these microscopes are used by professional scientists. Readings addressed the limitations of the SEM in that the instrument provides a topographical, black and white image of materials that are dry, dead and non-magnetic.

Middle-level teachers emphasized that for most students, the sixth grade year is the first time students are exposed to developing scientific procedural skills working with digital probes, software and microscopes to conduct scientific inquiries. Thus middle-level teachers expressed that they began planning their unit choosing five or six learning objectives, some of which involved learning about scientific procedures using instruments, how they work and how to use them. Their unit-plans included a number of station activities that directly addressed how microscopes are used in various disciplines of science to investigate specific questions.

For example, in their planning middle-level teachers organized scientific inquiry experiences beginning with videos and readings that describe applications of the SEM in medical science and research, computer technology and industry plus videos on how to operate each instrument to prepare students to work with the microscope. During each group of students’ first rotation on the microscopes, teachers drew upon language used in the videos and from the summer workshop and physically modeled how to use the SEM and Leica for small groups of students. Teachers then carefully observed each student using the microscopes to ensure that students did not break or damage the $75,000 SEM and to ask guiding questions such as “Why does the instrument raster the image before
moving into the SEM mode?,” or “Why do you think that material is shaped the way it is?” and “How would you describe the characteristics of that sample? Is it bumpy or smooth?” These types of questions followed an initiate, response, evaluate pattern intended to elicit student thinking at the remembering and understanding level, which involve so-called lower order thinking skills.

It was observed during the classroom observations and communicated by teachers in the CoRe call-out reflections and interviews that during the second rotation on the SEM, teachers used scientific vocabulary more specific to the learning objectives in their units. For example, teachers asked questions such as “What biological advantage do you think that the morphological characteristics you see provide to the plant that produces pollen that is shaped like that?” This question asked students to draw on prior knowledge to synthesize and evaluate data to create an evidence-based claim. Thus teachers intentionally combined the use of language and multiple experiences using the microscope to progressively scaffold students to move from lower order thinking involving one correct response to expand the scope of the unit to involve higher order levels of thinking to analyze and evaluate materials considering multiple characteristics of specimens. Teachers used questioning probes that so-called funneled students’ thinking and assisted the connection of the concepts addressed in this activity to the learning objectives involved in the unit.

Middle-level teachers also emphasized teaching and learning affordances related to the SEM itself. Several teachers expressed during the interviews and in their call-out
reflections that they viewed the use of the SEM as an opportunity to introduce students to
the micro and nanoscale, making comments such as:

My students were familiar with millimeter, centimeters, meters and as we use the Phenom [SEM] it’s a whole new world as we went into that microscale. So I think that this was something that was eye opening for us to move beyond millimeters, centimeters, meters using the tool to explore size and scale in way that is more visual, more concrete than if we just read about the ideas.

High school level teachers emphasized the idea in their unit-plans, CoRe tables and in group discussions captured in the workshop fieldnotes that successful science students should be able to draw on knowledge and skills learned at the middle-level related to scientific tools. As one high school teacher stated during the summer workshop “Students should be able to select a tool to meet a specific purpose and be able to identify sources of error on different types of instruments.” Most of the units of instruction developed by high school level teachers included fewer activities that explore how SEMs are used to do science up front in the unit and placed more emphasis on allowing students to explore the usefulness of the tool for various applications in science themselves. Following their initial experience working with the SEM, high school teachers then introduced readings and videos about the uses of nanoscale science and technology and facilitated class discussions about how the instrument may be useful in professional scientific laboratories or an engineering firm.

For example, one chemistry teacher wrote in his CoRe and shared during a classroom observation follow-up discussion that he wondered how effective the SEM would be in helping to determine the purity of samples based on how quickly electron charges built up on the material. He discussed with the class the idea that non-ferrous
metals in the SEM serve as a conduit to disperse electrons, so if there are metals in a sample, hypothetically the sample will charge more slowly in comparison to organic samples. During the focus group, this teacher shared that students in his classes found that the model of SEM they used that does not include elemental analytics is not a suitable instrument for measuring metal content in samples because the amount of electron charging on each specimen was inconsistent and difficult to measure and compare. Thus, the follow up conversation he facilitated with his students focused on what students learned about the data they were able to collect using the SEM, the data they were not able to collect and implications of this experience on professional scientific applications of the instrument.

Another high school teacher emphasized in his unit-plan and CoRe table the importance of using a variety of instruments in combination to analyze different aspects of materials in an engineering design application. For example, he asked students to use a stress and strain analyzer that measures the amount of force necessary to pull apart a metal sample. They then analyzed the break point of various materials used to construct bridges using the SEM and Leica to determine the characteristics of how each of the materials respond to force and how they break. Part of the final report required that students use professional engineering vocabulary to discuss how viewing materials at various scales contributed to their understanding of how three different materials respond to stress forces.

Science inquiry process. All of the units of instruction developed by members of the 2012 cohort involve teaching and learning science as inquiry within the scope of the
unit. This fact was determined in two ways: teachers specifically referred to their unit in writing and verbally as inquiry-based units of instruction and the Knowledge, Skills, Experiences, Learning Community and Assessment tool confirmed that all of the units fell somewhere within the inquiry continuum described by Marshall et al. (2009). Classroom observations, call-out reflections and interviews further confirmed that each unit included the primary elements that qualify a unit as an inquiry-based unit of instruction. Recall that the term *inquiry* in a general sense refers to the work that a scientist does when he or she studies the natural world connecting evidence with theory to support or refute claims or to make careful observations of concepts and processes. Students engaged in an inquiry process do much the same work as that of a professional scientist—they pose questions, plan investigations, review what is already known in light of experimental evidence, build a body of evidence that connects evidence to scientific knowledge, develop evidence-based arguments and communicate results (Martin-Hansen, 2002).

In their unit-plans, CoRe tables, interviews and informal discussions captured in the workshop fieldnotes teachers cited their decision to include the big idea of tools and instruments because the scientific tools provided through Project NANO provided to students the opportunity to explore real scientific questions and improve their understanding of concept and processes through observations made at multiple scales, both key dimensions of science as inquiry. It is important to note that given the context of the program in which the units of instruction were created, it is unsurprising that many of
the teachers' discussions placed strong emphasis on the affordances and limitations of
scientific tools used to conduct authentic scientific inquiries.

A widely held belief among all 23 of the participants is that because electron
microscopy is an increasingly ubiquitous technology, regardless of students’ future career
potential, all students should gain an understanding of the basics of how an SEM and
optical microscope can be used to conduct scientific inquiry. Teachers claimed during
workshop discussions that students should emerge from a nanoscale science unit with the
ability to explain how technology such as the SEM can change scientific explanations
and theories. Teachers shared their idea during the summer workshop and that scientific
tools and instruments such as the SEM and Leica optical microscope provide the
opportunity for students to apply the use of higher order thinking to conduct multiple
trials and compare data gathered in each run (specifically, working with SEM and Leica
images). Furthermore, teachers shared in their CoRe tables and call-out reflections that
this experience is important for students to conceptualize the value of multiple trials
required to build a body of evidence to refute or validate claims so that they could have
personal experiences that help them to conceptualize how the SEM can change scientific
explanations and theories rather than simply reading about the ideas. Participants also
emphasize the idea that the scope of the unit should include scientific inquiry experiences
using the SEM so as to be prepared to potentially pursue science and engineering career
opportunities that use electron microscopy.

Although there was a strong emphasis on structuring units in such a way that
would help to assure that students would have successful experiences learning about
nanoscale science and technology, each of the teachers (and the workshop instructors) pointed out during group discussions during the workshop and in their units of instruction and CoRe tables that working with scientific instruments takes time and patience and usually involves some element of frustration. As one teacher summarized during the workshop, “I designed an authentic scientific experience that involves patience rather than a canned experience where students are guaranteed to get the one correct answer because it’s important for students to understand that this is what it’s really like to do science.” During the workshop teachers spoke about the importance of having students figure out ways to solve ill-defined or unstructured problems because this is an important component of the science inquiry cycle. High school teachers wrote in their unit-plans and CoRe tables that they purposely designed their units to involve multiple problem solving opportunities that increased the potential for authentically frustrating experiences, whereas middle-level teachers wrote in their CoRe tables and shared during the workshop presentations that they included fewer potentially frustrating experiences to ensure that students developed a foundation of laboratory skills and self-efficacy in preparation for future challenges.

Interestingly, all of the teachers specifically mentioned in their units of instruction, CoRe tables, during conversations following classroom observations and in the interviews that they structured the laboratory stations involved in science inquiry to include multiple levels of cognitive demand. For example, they included stations that asked students to organize images of items from the largest to smallest to learn the concept known as powers of ten. One teacher shared during a classroom observation that
“The Power of Ten activity really requires low cognitive demand, but it’s fun and it ensures that kids understand this fundamental concept related to size and scale.” Another activity found in each of the units of instruction involved watching videos about SEMs and optical microscopes intending to prepare students to use each instrument. A middle-level teacher shared during an interview that “even though it’s not a really challenging activity, I want them to understand what they are doing when they get on the instruments so that they feel confident and are more likely to have a successful experience at the microscope.” Building upon this foundation of knowledge, teachers provided students with either written or verbal focusing questions intended to guide students to improve their ability to use scientific instruments to characterize, analyze and evaluate images they captured of specimens at various scales, and to synthesize these data by categorizing specimens, another activity that requires higher order thinking skills. Following a classroom observation one high school teacher shared, “I had kids draw what they saw in their images and practice using scientific language to label the parts to ensure that they understood that the microscope wasn’t doing the thinking to figure out how to characterize stuff, they were [doing the thinking].”

**Complementary technology.** In this section, I describe ways in which teachers described their metastrategic thinking about the use of complementary technology with the microscopes as a means for students to gather multiple forms of evidence in an inquiry process. One group of high school teachers spoke at length during the summer workshop planning process and in their CoRe writings about how using multiple scientific instruments provides students with the opportunity to develop multiple
experimental techniques. One veteran teacher described his thinking process during the focus group:

Once I looked at my learning goals, I looked around at what I had available to develop the stations, so I knew that I had a light sensor, so I knew I could develop a station around that piece of technology and we had some UV sensors, so we used that to create another station for the students to look at effectiveness of different sunscreen. I mean I started with my overall goal in mind and I could look at inquiry and I could look at content but then I figured ok, what materials and what other tools can I use to engage the students. Then I had to make sure that I had other pieces in there so that I had the ethical piece in there, besides content. And I was trying to put all that together under that unifying theme.

Two teachers specifically mentioned during the interviews that they felt more in control of the situation by integrating familiar technology to help balance their anxiety about working with students and new technology. Others emphasized the idea that integrating multiple technologies into the curriculum is necessary to as one teacher said, “build students’ 21st Century Skills.”

Complementary technology was utilized in a variety ways. Several teachers described in their unit-plans, CoRe tables and in interviews integrating the use of multiple existing digital and analogue tools such as instructional videos, online resources, Vernier probe ware and software, low-powered dissecting scopes, dissecting kits, hand lenses, safety equipment (such as gloves, goggles and fume hoods), ovens or window sills on the south side of the building used to desiccate samples, magnets used to test for ferrous metal and equipment brought to the classroom by teachers with earlier careers in science and engineering such as a stress and strain analyzer.

Simply learning about the use of multiple instruments and technical tools in an inquiry process and what can be done with them to collect and analyze multiple forms of
data was cited in their units of instruction during the workshop and in their unit-plans and CoRes as meeting specific state and district level science standards and authentically fulfilling a learning goal. Each unit of instruction involved three to eight learning objectives, every unit included the use of appropriate tools to complete an inquiry process as one of the learning objectives. A state science content standard every teacher cited is “based on observations and science principles, propose questions or hypotheses that can be examined through scientific investigation” and “Design and conduct a scientific investigation that uses appropriate tools and techniques to collect relevant data” (Oregon State Content Standards, 2009, p. 7). However, teachers did not design their units to be focused solely on technology but rather integrated instruments into the unit as tools useful to complete specific inquiry tasks.

Teachers shared during the workshop, in their units of instruction, CoRes, call-outs, focus group and interviews that they drew on technology to first teach students how to use technology in order to perform inquiry tasks. For example, teachers created instructional videos on how to use the SEM and Leica. One teacher shared the following during the focus group:

I did a couple of videos on the procedures, because I thought that the procedure for the SEM Phenom was way too cumbersome, I didn't read it [the workshop handout], and so the kids wouldn't read it. So I videotaped it [the SEM procedures] and I put in on the computer so the kids could watch it, and then I put it on YouTube. It's fresh, that's why it's all easy to remember. So we literally turned around that day, cause I was like I don't know how...these kids will forget it immediately after they learn it and I don't have time to test them on the procedure and do that jigsaw as was originally was planned, so I had my [student teacher] there and we did it. That's something that this summer...there should be another video done, you know concisely at a middle-level and maybe at a high school level so that you can have a different articulation, cause you still need to
keep it nice and clean for middle-level so they, they get the safety parts but they don't lose all of the different parts [of how to use the SEM controls].

Several teachers reported in their call-outs and in the focus groups and individual interviews that they provided doing whole-class demonstrations for how to load samples onto stubs and slides using an Elmo visual projector and large overhead screen. Teachers also connected the SEM to the overhead screen; however one teacher who did this said in the focus group and in his CoRe that he does not recommend over saturating students with un-interpreted views of other student groups’ various samples as this led to disengagement and boredom in his classes.

Other teachers used online discussion boards to facilitate group and class discussions on scientific topics and organize their group activities. A middle-level teacher explained during the focus group, “I used technology, for example a discussion board for the students to talk about ‘hey, this is what I focused on today,’ so that another student could then tie in the discussion with that other student and say ‘oh, that’s how it could fit these ideas with what I learned today.’” Teachers who report using discussion boards wrote in their call-outs that they felt that overall their students were better organized, stayed on task during class because each group member understood a specific deliverable he or she needed to produce that day and were better able to connect the content addressed at lab stations to the learning objectives. It is interesting to note that middle-level mid-career and veteran teachers said during interviews and in call-outs that they used their class website to convey instructions and to use discussion boards as an
instructional tool whereas high school teachers reported during interviews that they used their class website for one-way communication only from the teacher to the students.

Middle-level teachers utilized external web-based platforms for their unit as well. For example during the focus group one teacher spoke about the strategy he used to organize students’ photo micrograph files, “I used Media Fire…I used a six-month account for $24 that I was able to zip everything up right up to files where the kids would have access to that and I knew they were always there; that was nice not having to pony around these little USB cards.” The Media Fire accounts made the students fully responsible for managing their images and avoided the problem found in several classes where the SD card filled up quite quickly thus students lost microscope time running to the laptop station to download images to clear the card and prepare to capture more images. Another teacher who used the Media Fire account strategy specifically wrote lessons in his unit of instruction that required students to look at other groups’ images on Media Fire and write responses to a set of guiding questions in online discussions in preparation for in class discussions and conducting lab observations.

Both high school and middle-level teachers wrote in their call-outs and said during interviews, the focus group and during classroom observation follow-up discussions that they solved problems to do with the Leica SD card by using a fire wire and hooking the microscope directly up to laptops prepared with folders for each lab group to save their images directly into them. The computers were networked so that students could leave the microscope station and immediately go to another station and work with the Image J software or Photoshop to manipulate their images and make sure
that they clearly demonstrated the characteristics they wanted to bring to bear as supporting or refuting evidence. If they did not capture adequate images, then student knew to immediately sign up for another rotation on the Leica.

Teachers at both levels stated in interviews, in their units of instruction, CoRes and call-outs that they also drew upon Vernier probe ware and software as complementary technologies used in the inquiries. For example, one class of students did an inquiry examining different types of sunscreens to learn how they functioned to protect skin. The teacher of this class said in the focus group, “We did other experiments with light sensors so it was different experiments going on at the same time. And then we looked at different kinds of sunscreen and different types of particles we would see in those different kinds of sunscreen with the SEM.”

Both middle and high school level teachers wrote in their units of instruction, CoRes, call-outs and said in focus groups that they prepared students for working with the Leica by first involving first students in a unit that used low powered dissecting microscopes. As one teacher in the focus group reported:

I gave them some time to play with the dissecting microscopes before we started the unit so that they could look at parts of these things and decide like what part they wanted to focus in on and I think that this gave them an idea when I said that ok, you can look at like a leg, and that’s it! of the insect, yeah, that’s all you get is one leg and they were like, maybe I don’t want the leg, I said well, you have to decide because you know your limited in the amount of space [on the stub].

Teachers integrated the use of printed SEM photo micrographs to explain to students the concepts of size and scale. For example, several middle-level and high
school teachers reported that they employed an instructional method described by middle-level teachers during the focus group.

One other thing is that what I did is I took a piece of paper and I scanned it on top like the thick view. I put it on a side mount and I scanned it [with the SEM] at 400 x, 800 x, 1200 x and 2400 x and I printed out pictures so that they could see the scale of how thick it is, cause what I really wanted them to understand is that it doesn't matter how much you teach them about nanoscale or even micrometers, they don't understand how explosive this thing is so they see this little piece of paper and they can see how thick it is at 400x which is the minimum, they kind of get an idea like oh! Ok!

Nine teachers used models and simulations, another big idea in nanoscale science, in their unit of instruction. Each of these teachers communicated in their CoRes, call-outs and during the summer workshop that they had students create models and interact with online simulations because this approach appeals to visual and kinetic learners and tends to be a fun way to engage students’ interest and exploration of natural concepts and processes. Two groups of teachers that collaborated to create their unit wrote in their CoRes that models and simulations are useful to encourage students (and themselves) to dream about what is possible to study or create.

For example, an engineering design high school level teacher said following a classroom observation that he structured his unit to involve online simulations of bridge building to test structural materials for their capacities to withstand various forces. Based on what students learned about various building materials from stress and strain tests and examinations with the SEM and Leica, students input variables using calculations they had manually performed. After using the online simulation to test their theories, they then built physical scale-models of their bridges in class. Each group of students played the
role of a professional engineering design team and presented the model design and bid to a mock client.

The summer workshops each included multiple demonstrations using models and simulations. For example, each workshop included videos that showed scientists at work developing models in the fields of chemistry and physics to test ideas and understand natural processes. Although there is no conclusive evidence to suggest that this use of models in the workshop caused teachers to include models and simulations in the units they designed, it is interesting to note that nine teachers not only included models and simulations in their unit, but they also communicated in their CoRe, in the focus group and individual interviews and during the summer workshop that one of their reasons for doing so was to engage students by contextualizing science in the real world, providing students with the opportunity to learn how scientific tools and procedures are used by professionals to examine evidence in a well-equipped laboratory.

**Student engagement.** Another metastrategic idea that informs the research sub-question ‘of the nine “big ideas” in nanoscale science and technology, which are the big ideas that teachers choose to teach in their Project NANO unit and why?’ is the case relating to student engagement. Teachers in the summer workshop said that they thought about student engagement in terms of the “is it fun? test,” focusing the lesson on topics that are likely to be interesting and connected to an earlier unit, using proficiency-based education methods to engage students as partners in learning, and emphasizing the rare opportunity to work with expensive, research grade scientific instruments.
First, teachers cited their rationales for including the idea of “fun” as part of the selection criteria based on their PCK that having fun contributes to a higher level of student success because of increased levels of student engagement and feelings of self-efficacy. Participants report that they saw this situation as an opportunity to teach a unit that is likely to be of high interest to students in part because of the “wow factor” of seeing materials so “close up.” A common conversation among unit-planning groups was whether or not each of the choices of activities used to facilitate learning passed the, is it fun? test”.

For example, several life science teachers said during the workshop that insect anatomy is a high interest topic for many students building well on an earlier high interest unit, and tending to involve fun activities such as sampling aquatic macroinvertebrates (water insects) in streams. As one teacher put it “It combines the gross factor of bugs with the wow factor of seeing their parts really close up, so it is extra fun and engaging for kids.”

Teachers in the workshop were careful to point out that just because an activity is fun does not mean that the scientific procedures are not challenging, sometime tedious and often frustrating. Groups of teachers planning their units specifically discussed ideas of how to structure their units to include authentic problem solving challenges that require students to use critical thinking skills to move past that initial wow factor of the SEM; they included activities that helped students to understand not only what they were doing, but also understand the explicit learning goals expressing why they were to do each activity.
Second, based on the proficiency-based education approach, teachers in the workshop discussed the idea in their CoRes and interviews that when students are treated as full partners in their learning and given a high level of responsibility for keeping track of their learning, they are more likely to engage as participants in learning rather than passive recipients. Teachers wrote in their CoRes that one of the ways in which they thought that they treated students as partners in learning is that they structured their unit to provide repeated opportunities for the entire group to understand and think about the learning objectives and connected state content standard(s). Each teacher in the proficiency-based schools wrote that they posted the learning objectives for unit, the content standards they addressed and the daily learning targets in writing in a syllabus or work packet and on the bulletin or white board. At the beginning of each class most of the teachers ($N = 18$) planned a warm-up activity to assist students to understand the connections between the learning objectives, review the connected learning goals of prior activities in the course and how those goals connect with the activities planned for the day. This warm-up took the form of a quick write followed by a small group or whole class discussion in nearly every class.

In a few cases, teachers employed the use of exit slips that asked students to write how they thought the station activities related to the learning objectives. At the end of each class, the teachers who employed this instructional method said during interviews and in their call-outs that they collected the exit slips, organized them into categories and began the next class by sharing the categories of ideas found in the students’ writing from
the previous class period and providing discussion prompts to facilitate whole-group conversations.

One teacher shared during an interview that he structured class discussion questions by asking the entire class each of the questions so that everyone thought about the questions rather than directly posing the question to the student who wrote the exit slip. In this way, he tried to avoid the situation of having only one student think about the question and prepare a response. The teacher related that “nobody knew who I would call on, so they all knew that they should be prepared to answer each question.”

A third idea related to student engagement is that teachers emphasized in their CoRe tables that students are rarely trusted with expensive research grade scientific instruments. Several veteran teachers wrote that in their experience, access to research grade instruments inspires a serious response and high level of participation from students, depending upon how technology is integrated into the classroom. However, two teachers reported during classroom observations that they noticed that some students were intimidated by the expense of the SEM and did not use the instrument to its fullest capacity out of fear of breaking the machine. These teachers reported that they realized that they needed to figure out another way to communicate the importance of being careful with the instrument without intimidating students.

**Debunking students misconceptions.** Teachers wrote in their CoRes and unit-plans that they considered affordances and limitation of the microscopes to help students learn about the nature of science and to challenge misconceptions in science also known as alternative conceptions. Opportunities to debunk misconceptions that teachers wrote or
spoke about were: misconceptions about the nature of science, misconceptions that lead to an over-dependence on technology, opportunities to avoid bad laboratory habits that student misconceive as being good practice.

Several middle-level teachers wrote in their CoRes and shared during workshop discussions, during classroom observations and interviews that they thought about using the instruments as a way to debunk students’ misconceptions about the nature of science. To do so, they employed the SEM and Leica as observation stations rather than using the instruments to collect data to support a claim or hypothesis. As one middle-level teacher put it during an interview, “I want to debunk the idea that there is only one scientific method of discovery.” This teacher stated that the Oregon Department of Education science work sample scoring guide can reiterate common misconceptions related to “the scientific method,” and that “unfortunate phrasing” may lead to a more narrow view of the nature of science on the part of teachers as well as learners. A high school level teacher followed up on this comment and stated that she wanted to demonstrate to both her students and anyone who may read her Resource Folio that using the SEM and Leica microscopes to examine and characterize materials with both qualitative and quantitative methods is an authentic approach to learning about the natural world even if no hypothesis is generated and tested.

Teachers reported in their CoRe tables that the structure of their units was highly influenced by the opportunity to combine the use of high and low technology to examine samples as a way of “debunking students’ tendency to focus on the computer to provide the answer rather than recognizing the underlying technology married with computing
ability” (high school engineering design teacher). Teachers spoke at length during the summer workshop, classroom observations and interviews about students’ alternative conceptions and even temptations of allowing technology “to do the thinking for you” and the dangers of “becoming so enamored with technology that the only thing that students learn is how to operate the technology and how the technology works” (high school engineering design teacher) and thus, they miss out on learning the science content the teacher intends for students to learn while using the instrument.

Therefore, teachers reported in their CoRe tables, unit-plans during interviews and classroom observation follow-up conversations and during their workshop final presentations on their unit that they drew upon a variety of strategies intended to assist students to avoid developing an over-dependence on technology. For instance, an engineering design high school level teacher said following a classroom observation that he required his students to solve mathematical equations related to material stress and strain by hand rather than using a calculator to solve problems so that his students would understand how and when to apply particular algorithms and formulas using higher order thinking skills to problem solve. A middle-level teacher shared in the focus group that he structured the examination of samples so that, “students would look at objects from varying distances from across the room, half-way across the room, up close, using dissecting microscopes, then to about 30x and then finally to the nano.” His students, 

…got to pick something which they could see conceivably from across the room to zoom in on and if it was something small like a flea, we started off with drawing a stuffed squirrel. A drawing of the squirrel we put out there, then the hair of the squirrel and then the flea.
Thus, he claimed that his students understood the value of examining samples and describing characteristics that are noticeable at each scale and avoided the problem of thinking that technology can do everything and missing certain features that are not detectable at higher levels of magnification.

All of the participants spoke or wrote about the idea that working with scientific tools provides a guided opportunity for students to properly learn complex scientific content and procedures as preparation for higher-level course work. During the summer workshop and interviews they spoke about the opportunity to teach students correct procedures before “they learn bad habits, short-cuts or work-arounds that don’t work when they move up to more complex inquiries (middle-level teacher).” During the interviews teachers said that students often mistakenly believe that their poor procedural habits do not matter; teachers viewed the Project NANO unit as an opportunity to demonstrate that procedures such as proper sample preparation, diagramming the position of samples on a stub or slide, and labeling images is critical to the scientific process.

Both middle-level and high school life science teachers communicated during the workshop and in their CoRe tables that microscopes were useful for examining physical characteristics to provide context for correctly understanding evolutionary advantages of particular adaptations of species. Most of the teachers also reported in their CoRe tables that the use of microscopes provided the opportunity for students to observe repeats of patterns found in nature and to consider if there is a functional role of those structures. For example one teacher said in her CoRe:
By becoming familiar with the structure of organisms, students are better able to understand that functionality comes from the structure of components working together as a system…this experience provides learners with the opportunity to visually debunk misconceptions such as the common mistaken idea that all living tissues are the same or that the tissues of non-human organisms such as insects are very simple. Students may compare how pieces of an organism fit together, how the parts functions together to and consider the evolutionary advantages of various adaptations.

For instance, students compared feathers, fur and scales and thought about the morphological characteristics of each and the pressures that may have caused the development of each of these adaptations and why these adaptations increase the rates of reproduction (biological success) in various species that have these features.

During the summer workshop and in their CoRe tables teachers shared that their students often have deeply rooted misconceptions about why species are formed the way they are and that humans are not the only species that impact the environments they live in. Life science teachers report that viewing specimens under the microscopes may illuminate for students the relationships of phenotype and genotype by examining the relationship between leaf stomata and photosynthesis, or structural characteristics of diatoms to consider the idea of diatoms as bio-indicators related to the health of the habitat. They may also view specimens that have physical indications of disruption (such as the thinning of egg shells due to exposure to chemical contaminants). Thus, tools and instruments provide the opportunity for an interdisciplinary understanding of the natural world by considering the interplay between chemical and physical pressures that shape life and how life itself may shape the environment.
Students’ learning styles. A repeated metastrategic idea found in the CoRe tables, unit of instruction, workshop discussions and interviews is that of including experiences in the unit that involve multiple learning modalities within the scope of the unit that appeal to various learning styles to improve students’ abilities to conceptualize size and scale and the structure of matter.

Teachers repeatedly pointed out that they think that there are as many learning styles as there are students in their classes. Most of the teachers described what they meant by the term learning styles by referring to kinesthetic, visual and audio learning styles. Several of the teachers referred to learning styles in terms of describing a cycle of learning wherein students move through stages beginning with concrete experiences, reflective observation, abstract conceptualization and active experimentation. The examples they chose to describe their ideas appeared to fit with Kolb’s Learning Cycle (Kolb, 1984; McLeod, 2010), which is based on experiential learning theory that views learning as a process involving iterative steps and continuous modification of ideas as a result of experience. Although Kolb developed this model as part of adult learning theory, the ideas contained in the model are useful for this situation because they appear to accurately capture ideas expressed by the teachers in this study related to how they think about their students' cycle of learning. Figure 11 depicts Kolb’s Learning Styles.
Teachers said in their CoRe tables and during the classroom observations and interviews that they also adapted the order of activities to accommodate different students’ styles of processing. They considered the idea of adapting lessons to meet the needs of learners who best conceptualize ideas by starting with the big picture and then filling in the details (whole-to-parts learners) and the needs of the more linear, progressive learners (parts-to-whole learners) who respond well to a gradual building of small pieces of information leading to a description of the whole concept. This group of teachers spoke about using the concepts of size and scale to “scaffold the unit.”
The idea of *instructional scaffolding* relates to Vygotsky’s (1978) zone of proximal development concept and refers to the supports given to students during the learning process with the intention of helping students achieve learning goals without reducing the nature or difficulty level of tasks. The teachers’ description of the idea of scaffolding can be characterized as a broad concept that encompass more than simply the idea of “chunking” ideas into small constitute parts.

For example, one participant argued with his group during the summer workshop that thinking broadly about scaffolding from multiple directions is important to ensure a high level of student engagement for multiple learning styles and to ensure that students understand how Aristotle’s idea *the whole is greater than the sum of its parts* applies when one is working to conceptualize how size and scale and size dependent properties relate to one another. This group of teachers’ unit of instruction included stations that have varying levels of cognitive demand and optional extension activities. The stations varied in that the teachers described in their unit of instruction and CoRe that some stations were best for parts-to-whole and others best for whole-to-parts type of learners. During the summer workshop planning session one teacher in this group said that all of the stations he designed demand a high level of independent critical thinking to solve problems and provide various forms of supports designed to function as interactive conduits used to guide learning experiences and social interaction.

**Emphasis on the constructs of size and scale and structure of matter.** Due to the nature of Project NANO, it was found in the unit-plans that teachers created that all of the teachers developed units that involved activities to investigate the concepts of size
and scale and the structure of matter. Interestingly, all of the teachers emphasized in their CoRe tables the affordances of the technology to investigate the ideas of size and scale and structure of matter, which they viewed as fundamental constructs necessary for understanding key ideas that students will approach later in their course, in higher grades and in college.

Every unit emphasized the use of tools and instruments to observe and characterize the morphology of specimens at various scales in order to compare and contrast features. Every unit also included a powers of ten activity wherein students conceptualized size and scale by ordering a series of objects from large to small sizes. Many teachers used online versions of the powers of ten activity that they found on their own rather than the printed cards demonstrated at the summer workshop.

In comparison to size and scale, teachers were more discipline and grade level specific in describing their rationales for including ideas related to the structure of matter. What they had in common was that they described the inclusion of this concept as a way to meet science content standards using multiple ways to interact with technology involving digital, analogue and online resources. Again, middle-level and high school life science teachers’ units of instruction focused on structure and function of matter state content standards. High school physics and chemistry teachers units focused on interaction and change state content standards related to the structure of matter.

For example, multiple high school chemistry teachers communicated during the summer workshop and during interviews that they chose to focus on the big idea of structure of matter because students would be able to use the microscopes to see the
qualitative differences between mixtures, colloids and suspensions, categorize elements in the sample, characterize the purity of the sample and determine percent composition. Those teaching life sciences wrote in their unit-plans and CoRes that they focused their lessons on examining part of plants or insects to facilitate students’ conceptualization of the relationships between genotypes and phenotypes and the pressures that influence changes to the morphology of species and their environment.

**Summary of the affordances of scientific tools and instruments.** The Next Generation Science Standards (Achieve, 2013) asks teachers to think in new ways about how to approach designing units. Whereas teachers have traditionally focused the majority of their attention on disciplinary core ideas and classroom management concerns, the new science standards ask teachers to structure units to “reflect the interconnected nature of science as it is practiced and experienced in the real world” (p. 1). The teachers involved in this study demonstrated that they are in the process of shifting their metastrategic thinking related to defining the scope of their unit to link science and engineering practices, cross-cutting concepts and disciplinary ideas by drawing upon the affordances of technology and tools.

**The influence of state science content standards.** In this section, I present how teachers considered the role of science standards as they determined the scope of their unit. Table 6 presents teachers’ metastrategic thinking related to the scope of the unit and the influence of state science content standards.
Table 6

*Teachers' Metastrategic Thinking; The Influence of State Science Content Standards*

<table>
<thead>
<tr>
<th>Planning the Unit</th>
<th>Factors of Thinking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scope of Unit</td>
<td>The Influence of State Science Content Standards</td>
</tr>
<tr>
<td></td>
<td>• Established learning objective, big ideas in nanoscale science and selected appropriate state standards</td>
</tr>
</tbody>
</table>

Early in the development of their CoRe tables at the summer workshops, teachers referred to state and local science content standards to define the scope of their units by choosing three to eight learning objectives and big ideas in nanoscale science. Groups also drew upon the Framework for K-12 Education (NRC, 2012) to consider core ideas including cross-cutting concepts and practices in science and engineering. Thus, the consideration of standards played a central role in their decision-making process. From there, it was a matter of backward planning (Wiggins & McTighe, 2006) using the CoRe table and unit-planning template to, as one high school teacher phrased it "scaffold lessons from the science standards" as they planned lessons.

It is important to note that from this point in the planning, I observed during the workshop that teachers did not think about the development of their units as a linear process, but rather as an iterative, cyclical planning experience. Instead, their conversations looped as each group member brought revised lesson plans to the group for discussion and they reconsidered how the activities addressed science standards and specific learning objectives.
Each unit-plan used a focusing question or set of questions that closely relate to a set of state and district science content standards and fit within district or their schools adopted curriculum. For example, a group of teachers reported during the summer workshop and post classroom observation discussion that the unit they developed augments the Science Education for Public Understanding curriculum unit on structure and function related to fossils, natural selection and adaptations. Teachers selected the learning objectives and big ideas in nanoscale science they would use to focus the unit based on the how well those ideas fit with the standards they chose and with the idea of augmenting the curriculum by integrating experiences with the microscopes into a unit that covers concepts that are according to one teacher in the workshop “difficult for students to conceptualize without a visual experience and hands-on experience.”

During the summer workshop, focus group and interviews the 13 teachers who chose to include the big idea forces and interactions each cited science content standards as influencing their metastrategic thinking to include these ideas in their unit of instruction. Here again, teachers chose state content standards that are discipline and in some cases, topic specific.

High school physics and engineering teachers said during the workshop and in their CoRe tables and unit-plans that they included the big idea of forces and interaction to help students to understand relationships between how things work, how they are made and how the SEM may be used in these disciplines to examine natural processes related to materials. For instance, one teacher wrote in his unit-plan and CoRe about using the SEM to examine the concept of friction as including both roughness and smoothness of
materials. This teacher stated that a visual experience of working with various microscopes to examine materials may assist students with testing their own conceptions and debunking misconceptions such as that idea that friction is caused only by the roughness of material. He noted that looking at materials under the microscope could assist students to understand that friction is generated on smooth surfaces too by looking at the stickiness of a material under a microscope to conceptualize static attraction.

A group of high school biology teachers wrote in their CoRe tables that they included forces and interaction in their unit-plans as a key big idea found in the state standards because the opportunity to visually interact with specimens at various scales may assist students with testing their conceptions about matter. For example, teachers drew upon their PCK that visual experiences may help students to understand that pollen is dispersed in multiple ways as a result of natural selection and biological adaptions.

Several teachers developed a unit on pollen. One of the members of the group said during the workshop that the gross details of the pollen morphology can be observed with the compound [optical] microscope but “the SEM gives the details to see subtle structural differences that provide clues to how different types of pollen are dispersed.”

Nine teachers included the big idea of size dependent properties in their units of instruction citing science content standards in their CoRe table and during workshop discussions as the motivation for this choice. Interestingly, the physics and chemistry teachers cited very different content standards as their rationale for their choices. For example, on one hand, two physics teachers said during the workshop and in their CoRe tables that the SEM provides students with an opportunity to study a physics application
related to light refraction and reflection by examining butterfly wings at various scales including hand samples held up to lights at various angles. On the other hand, several chemistry teachers expressed during the workshop and following classroom observations that using the SEM is an opportunity to relate to students how drawing upon both chemistry and physics concepts illuminates a concept to a greater degree than if one were to consider ideas that are traditionally associated with only one or the other of the disciplines. The example this group of teachers used is the Z-contrast microscopic technique used to examine pigments in moth wings that indicate elemental differences on the wing for structural determination. Although the Z-contrast technique involves quantum mechanics, the teachers did not specifically communicate a conceptual connection between ways to view pigment and quantum mechanics, but rather remained focused on the big idea of size dependent properties throughout their discussions and in their writing on their unit-plan and CoRe tables.

Science, technology, and society. In some way, every participant addressed the ideas of science, technology and society in their unit-plans. For example, every teacher showed videos on research and development and current applications of nanoscale technology in medicine and industrial applications of nanofilms, nanowires/nanorods in technologies such as photovoltaic devices and computer chips. Table 7 presents teachers' metastrategic thinking related to science, technology and society. The category of metastrategic thinking in this table is planning the scope of the unit and three factors of thinking that are associated with this category.
Table 7

*Teachers’ Metastrategic Thinking Related to Science, Technology, and Society*

<table>
<thead>
<tr>
<th>Planning the Unit</th>
<th>Factors of Thinking</th>
</tr>
</thead>
</table>
| Scope of Unit     | Science, Technology, and Society  
|                   | o Bioethics  
|                   | o Potential dangers of nanoparticles  
|                   | o Human health  
|                   | o Environmental health |

Teachers were observed during the workshop and also wrote in their CoRes and call-outs that they collaborated online to find and share age-appropriate materials related to science, technology and society that fit the scope of their unit. One high school chemistry and biology teacher shared during her interview that she chose an article from the Project NANO Media Fire website “that describes nanotechnology applications related to the prom dress of the future” based on her metastrategic thinking that this article fit the learning objectives related to form and function that she covered in her biology unit.

**Bioethics.** Fourteen of the 23 participants covered the topics in their unit of instruction related to the effects of nanoscale science and technology and bio-ethics in their unit-plans as part of the big idea of science, technology and society. These teachers drew extensively on articles, videos, and facilitated class discussions with guiding question prompts, reflective writing exercises and laboratory experiences. During the workshop discussions, in call-out reflections and follow-up interviews each of these teachers emphasized their idea that bio-ethics fits as a core component within the scope
of their unit because of the opportunity to use the microscopes to reinforce ideas found in the readings and videos with tangible evidence. For example, during the summer workshop, one life sciences teacher who was designing a marine sciences unit spoke about his idea to ask students to compare the morphology of well-formed and deformed aquatic insects, read an article on potential unintended consequences of releasing human-modified molecules into the environment and then engage in a class discussion on genetic mutations that lead to physical deformities in species.

**Potential danger of nanoparticles.** Fourteen of the 23 units included lessons in their unit-plans on the ideas that what we cannot see might hurt us and that human-altered molecules that we cannot control may disturb the web of life, not just human-life. Teachers reported during the workshops that they felt strongly that students understand that humans cannot conceptualize the full impact of nanoparticles over the entire life span of manufactured materials and that nanoparticles that enter a body or are otherwise released into the environment have unforeseen impacts on natural systems.

**Human health.** Teachers representing each discipline and grade level of science taught at the secondary level pointed out during workshops and interviews that many of their students may not have considered the implications of consumer choices on human health. These teachers stated that it is critical that students understand the potential benefits and costs of nanoscale science and technology related to human health so that they will become empowered to make informed decisions about the products they purchase and use and to contribute as citizens to the political process related to policy development and the manipulation of matter at the molecular level.
Environmental health effects of nanoscale science and technology. Most of the life science and chemistry teachers emphasized in their unit-plans and CoRe tables the importance of integrating readings, videos and station activities addressing potential environmental health effects of nanoscale science and technology. One teacher said in her CoRe table that “understanding how organisms interact with their environment will give students a better understanding of the consequences of changes to an environment, so let them see!” Again, this statement is a representative example of teacher communicating a rationale for the choice to fit within the scope of the unit the big idea of science, technology and society as a learning objective because of the teacher’s experience of observing the power of pairing direct instruction with a guided inquiry experience examining concepts related to environmental health. For instance, a high school biology teacher involved in stream restoration described during the workshop the power of seeing pollution in the tiny nooks of a diatom or seeing deformities of an insect taken from polluted water and as a way to emphasize and reinforce ideas expressed in articles and videos about the effects of acid rain and non-point source pollution on aquatic ecosystems. She said during the follow-up interview and in discussions following classroom observations that she planned to build on this activity by adding readings and discussions of what scientists do not know about the effects of releasing human-manipulated molecules into water systems.

This concludes the section related to teachers’ metastrategic thinking related to defining the scope of their unit. Next, I present teachers’ metastrategic thinking that
informed their choices for how to sequence the nanoscale unit within the scope of their science course or courses.

**Sequence of the unit within the science course.** The participants expressed a number of factors that influenced their thinking related to how they chose to sequence the unit within the science course. This section addresses the type of unit teachers selected, the influence of limitations on their decisions and factors that involve both affordances and limitations that influenced how they designed their units of instruction. I begin with a report on teachers’ metastrategic thinking related to the types of units teachers developed and how these units are sequenced within the science courses. Table 8 presents teachers’ metastrategic thinking related to planning the sequence of the unit of instruction with the science course. The table lists six factors of teachers thinking which I describe below.

**Table 8**

**Teacher’s Metastrategic Think About the Type of Unit**

<table>
<thead>
<tr>
<th>Planning the Unit</th>
<th>Factors of Thinking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sequence of unit within the science course</td>
<td>Type of Unit</td>
</tr>
<tr>
<td></td>
<td>o End of a unit</td>
</tr>
<tr>
<td></td>
<td>o Extension unit used to reinforce ideas</td>
</tr>
<tr>
<td></td>
<td>o Conceptual bridge between units</td>
</tr>
<tr>
<td></td>
<td>o Out-of-sequence unit</td>
</tr>
<tr>
<td></td>
<td>o Influence of the time of year on choice of topics</td>
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<tr>
<td></td>
<td>o Consideration of instructional techniques</td>
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</tbody>
</table>

All of the teachers said during the workshop or in their CoRe table that they considered the time of the year they were likely to be able to reserve the SEM and Leica, the content and units they normally teach at that time of year and other technologies
available at their school they would be likely to be able to access at the same time they borrowed the SEM and Leica. From there, teachers determined they type of unit they wanted to teach. The type of units that teachers planned are: an extension to an earlier unit, the end of an instructional unit, sequencing the unit to provide a conceptual bridge between two units, enhancing an existing unit taught at a particular time of the year, and planning the unit as a stand-alone unit due to the limited availability of the SEM and Leica.

Two teachers who designed their unit as extensions wrote in their CoRe tables and said during interviews that they choose to focus on topics from an earlier unit they knew students might have difficulty with to reinforce ideas and provide students with another opportunity to learn concepts such as size and scale from a different perspective using scientific tools and instruments. One teacher related during an interview:

We were finishing up our Ecology unit so, for the past 18 weeks we've been looking at ecology concepts with our sixth graders. [We] started the year with outdoor school and then continued to look at ecology concepts and this is an end-of-ecology unit. Almost all my groups were engaged, but they also got to pick pretty much what they wanted to look at, which was one of the things that I really wanted to give them some play time with this, some exploring time and discovery time and I kind of thought well I'm going to throw this unit in here, it doesn't really fit beautifully with everything else were doing, so it would be nice to kind of give them a chance to do some exploration of materials and the ideas of size and scale. And so that was one of the things that I was really kind of keen on.

Another teacher wrote in his CoRe that he used the Project NANO unit as a conceptual bridge “to generate interest and introduce students to ideas related to constructive and destructive forces in nature at any scale.” The unit served as a conceptual bridge between two units to strengthen students’ understanding of two
fundamental concepts in engineering. This teacher elaborated during an interview that he chose to sequence the unit to prepare students for tensile strength engineering lessons that depend upon students have a clear understanding of stress and strain to be successful.

Similarly, a high school biology teacher wrote in her CoRe table that she chose to situate the Project NANO unit as an introduction to more complex ideas related to structure and function of the stomata and the role of abscisic acid, a plant hormone, in opening and closing the stomata covered in IB Biology. Thus, the learning objectives included in the unit were limited to those that would suit this purpose.

In order to enhance existing regular units, two groups of middle-level teachers decided to reserve the SEM in the early fall when they were to teach particular scientific protocols and procedures to their sixth grade science students. During the summer workshop they said that they chose to adapt a decade-old forensic science unit that they have traditionally taught at the beginning of the school year to lay a foundation of developing students’ understanding of scientific procedures and learning how to follow scientific protocols. These teachers said that because the emphasis of the forensic science unit was on the tools of science, integrating the SEM and Leica into the rotation of stations “presented an apparently seamless integration into the fall science curriculum.”

Finally, during the workshop, interviews and focus group discussion several teachers said that they figured out how to sequence their unit by first determining the focus of the scientific inquiry they wanted to do with their students and then they figured out when in the academic year such an investigation might fit into the curriculum. Some of the teachers’ inquiry questions were influenced by the season. They said that they also
referred to the state science standards to consider how to scaffold learning experiences that would support students to be ready to approach more complex standards later in the course.

Some of the teachers’ wrote in their CoRe and shared during workshop discussions that their inquiry questions were influenced by the season. Given that teachers took the workshop during the summer, some teachers reported during the summer workshop and during the interviews that they chose to use this opportunity to explore questions of high interest to themselves that they thought may appeal to their students as well, especially questions related to a hobby in which they participate in the summer or related to their own scientific questions concerning products used more often in the summer, such as sun screen.

For example, one teacher said that he lives near a bridge that is being completely renovated. During the summer he frequently rode his bike over that bridge. After class on the first day of the summer workshop he rode his bike across that bridge and thought about the idea that “students really only pay attention to what they can see and engage [with], everything else they memorize. Here is a tool for students to engage with anything solid at the nano level.” This teacher said during his presentation on his unit at the summer workshop that he designed a unit based on his own curiosity about the choice of metals that would be used to rebuild the bridge in comparison to the materials that are currently part of the bridge and how materials respond to various forces such as stress and strain. He added during an interview that he designed the unit with awareness that a tactile and visual experience might support students’ abilities to conceptualize complex
physical relationships and that mastery of these topics would be useful for learning more advanced ideas.

An element of the workshop that may have influenced teachers’ decisions about how to sequence the unit within their courses was the process of peer review of units of instruction. For example, on the third day of each of the workshops, participants from the prior year were invited to share their own Project NANO units using a Critical Friends tuning protocol (Blythe, Allan, & Powell, 1999). Following the tuning protocol discussion, groups of teachers were observed developing lists of the elements addressed in the sample lessons and criteria of analysis for determining the effectiveness of various activities to meet the desired learning outcome goals. They then considered their own draft unit-plans and debated how to maximize the effectiveness of the unit by planning out an achievable scope and sequence for the unit. Throughout this and other group-work experiences that took place during the summer workshops, teachers said that they were inspired by materials that were brought into the class by the instructors or classmates such as the state and national science content standards, *Uncovering Student Ideas in Science* series, *Science, Formative Assessment; 75 Practical Strategies for Linking Assessment, Instruction, and Learning* (Keeley, 2008), links to websites such as the Nanosense.org and Nano.gov, a book filled with high quality nanoscale images giving teachers ideas about materials that image well and exemplify points they want to make using visual tools, and Curriculum Topic Study resources such as the AAAS (1994) Atlas of Science (concept maps) that provide visual diagrams of how concepts connect and Science Matters (Hazen & Trefil, 2009).
Several teachers excitedly reported during the summer workshops that their choices of the learning objectives and big ideas in nanoscale science were strongly influenced by access to specific types of materials. One teacher related during the focus group that “the book filled with nanoscale images inspired lots of ideas about what images well, what is interesting to look at with an SEM and ways that color can be added with the Image-J software to emphasize particular characteristics on a sample.” The co-instructors and teacher participants brought samples to the workshops and shared their metastrategic thoughts about scientific topics these samples may be used to teach. Some examples of samples that teachers brought to the workshop were: insect parts, hair, feathers, bacterial mats and diatoms to investigate topics related to evolution and adaptations; human teeth, animal teeth, guitar strings, metal bolts and razor blades used to investigate form and function and how material wear and degrade, metal “dog-bones” used by engineers to test material strength, mixtures, colloids and suspensions used to investigate homogenous and heterogeneous substances and dust samples used to examine the composition of dust found in different rooms of a home as part of a lesson focused on the development of scientific procedures and inquiry skills.

One high school teacher shared during an interview that she was inspired by a story she heard at the workshop about another teacher who asked a researcher for samples her students could examine with the SEM. This teacher contacted a local college level researcher who responded to her request for information about gecko feet by sending her mounted SEM stubs with gecko’s feet, which afforded her students with the opportunity to design a study of Van der Waal forces. From there, the high school teacher said that
she looked in her science curriculum to figure out when she would cover Van der Waal’s forces and scheduled the SEM based on this timing.

Another frequently reported metastrategic thought that was shared during the interviews was that teachers teamed up with other participants who had a good idea for a unit rather than working to find an original idea or struggling with a different idea that may have been more difficult to develop into a unit. In many of these cases, teachers decided together that their unit would be more successful if they involved examining samples that either do not charge too much or could be coated to avoid electron charging. Again, the term “charging” refers to a build-up of electrons in an area of a sample which causes that area to become bright white and therefore does not image well because the details of the sample are either washed out or indiscernible. In some cases, the new idea did not necessarily fit logically into the curriculum during the period that the instruments were available to borrow. Thus, teachers had the choice to either postpone teaching the unit until next year or teach the unit out of sequence. Three teachers of the 23 shared in emails to the researcher that they made the choice to wait until next year to teach their unit and two teachers chose to teach their Project NANO unit as a stand-alone that did not fit into a logical sequential order within the greater lesson cycle of the course.

**The influence of limitations.** Teachers shared during the summer workshops and CoRe tables three ideas that they viewed as limitations that influenced how they designed the Project NANO unit of instruction. Table 9 presents factors of teachers’ thinking related to limitations they considered with planning the sequence of their units. These are the limitations of the SEM itself, teachers’ views of students’ developmental limitations
regarding student capacities for interpretation of scientific observations, and time constraints.

Table 9

*Teachers’ Metastrategic Think About the Influence of Limitations*

<table>
<thead>
<tr>
<th>Planning the Unit</th>
<th>Factors of Thinking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sequence of unit within the science course</td>
<td>Limiting Conditions</td>
</tr>
<tr>
<td></td>
<td>o The SEM</td>
</tr>
<tr>
<td></td>
<td>o Students’ development</td>
</tr>
<tr>
<td></td>
<td>o Increased class sizes</td>
</tr>
<tr>
<td></td>
<td>o Time</td>
</tr>
</tbody>
</table>

**SEM.** I begin by describing the influence of the limitations of the SEM. Samples put in the SEM must be dry and non-magnetic. Samples that contain a high percentage of organic material tend to charge quickly which means that without a conduit, electrons build up on a section of a sample and obscure the image. As teachers in the workshop experimented with samples, they found that some samples are difficult to dry or could not be dried in time for class, such as snake skin that contains a high percentage of oil content and cannot be dried quickly without the proper equipment. Similarly teachers found that some samples were much too big for the SEM and, therefore, would not work for their unit of instruction. Therefore, teachers switched to a different topic, in some cases at the last minute, so that the samples they chose would work with the SEM and, therefore, the students would be more likely to have a successful experience.
Teachers also reported in their CoRe tables, during classroom observations and interviews that they deeply considered what is possible to do with or without trained adult volunteers supervising activities such as scientific procedures that expose students to potential dangers or complex activities that require guidance. For example, teachers who said that they work with learners with lower-than-average abilities or with middle-level students considered that because they thought of themselves as being “stuck” at the SEM during the lab rotations, they needed to have an adult volunteer to assist students with interpreting the directions for how to use the Leica’s functions including the digital capture function and how to complete the laboratory assignment for that microscope station. One of these teachers said during an interview that without an adult volunteer, she felt that she “had better not include the digital capture function on the Leica” because she thought that her students were “likely to have an unsuccessful experience with that microscope without adult assistance.”

**Students' development.** Teachers also wrote in their CoRes and said during the focus group and individual interviews that they considered the sequence of skills building that students experienced and then planned boundaries of inquiries based on what students were likely to know and know how to do and based on what was feasible to accomplish within the scope of the unit. For example, teachers said during the workshop and wrote in their CoRes that they were influenced by the story told by one of the summer workshop instructors about “a very bright high school chemistry student who decided to investigate the composition of the particulates captured in the filter of the air duct in the classroom.” The student quickly realized that there were so many different
types of materials found in the air return duct filters that it became a totally overwhelming task to characterize each material, classify those materials and then determine the percent of the composition found on the filter. This student stopped coming to class because he was mortified by his inability to carry out the task he had set for himself. After a couple of days, the teacher recognized the problem and helped the student to reframe his question and reorganized the task to make the project possible for the student to complete in the time remaining in the unit.

The summer workshop instructors drew upon this story to encourage teachers to narrow the focus of their units to avoid overwhelming students. They suggested limiting investigations to examining the biggest components or features in a sample (not the anomalies in a sample), imaging known characteristics and identifying major constitute parts. Several teachers reported during classroom observations and interviews that this story influenced their thinking and caused them to limit the number of learning objectives included in their units and in the case of open-ended inquiries, to guide student to choose simple inquiries.

Teachers reported during the workshop, in their CoRes and during interviews that they thought a great deal about students’ abilities and limitations at different developmental stages and based on these reflections, they refined the scope of their units, as they designed activities to meet each learning objective. For example, one high school chemistry teacher recounted during the focus group discussion that she and her group designed the placement of activity stations in relation to where the teachers would be
throughout most of the unit (near the SEM) based on the level of cognitive demand of
each of the activities involved in the station:

When we designed our lab stations, some of our lab stations were designed that
required more help than others; some of them [the lab stations] were things like
the Powers of Ten puzzle, where kids could do them, conceivably, on their own
whereas other activities were more challenging and kids might need help to figure
them out.

**Class sizes.** Another limitation that influenced teachers’ choices of learning
objectives and sequencing of activities in the unit was the awareness that due to school
budget cuts, many of their class sizes were going to expand from an average of 28
students to 43 or more students per class. During the workshops and interviews teachers
related that due to large class sizes they decided to “flip the unit” by designing activities
that could be accomplished at home such as watching nanoscale science informational
videos and reading articles as homework or during study hall so that lab groups could
better utilize the limited amount of time that the SEM and Leica would be in their
classrooms. Teachers shared their idea during interviews that this decision narrowed their
choices of activities to include in the unit, which in turn, narrowed their selection of
learning objectives to include in the final design of the unit. Again, this is another
example of how unit-planning was not a linear process, but rather a cyclical process as
new information and ideas informed refinement of teachers’ plans.

Other teachers said during classroom observations and in interviews that they
chose lab activities that have a low level of cognitive demand to set up as stations on the
opposite side of the classroom from the SEM because they knew that students would be
working independently at those stations since the teacher would be either stuck at the
SEM or otherwise unable to rotate through the stations to help each group exactly when they needed help. They set up more demanding activities near to the SEM where the teacher knew that she or he would be more able to help students when needed.

**Time.** Finally, as mentioned above, the fact that there are only two SEMs and Leica microscopes available to check out to three years of cohorts in the program limited teachers thinking about how to sequence their unit within their courses. Teachers who were not lucky enough to schedule the Project NANO toolkit during a period when the unit they designed would be logically sequenced within the academic year were given the choice to wait until next year to teach their unit, redesign their unit or teach their Project NANO unit out of sequence with the greater learning cycle.

**Factors That Involve Elements of Both Affordances and Limitations.** Although it is the case that many of the preceding ideas in this section could be viewed as factors that have elements of both affordances and limitations, I have noted limitations in the way that teachers described them. Here, I report factors that teachers specifically described as those that have elements of both affordances and limitations beginning with a graphical depiction in Table 10 on the next page.
Table 10

*Teachers’ Metastrategic Thinking About Factors that Involve Both Affordances and Limitations*

<table>
<thead>
<tr>
<th>Planning the Unit</th>
<th>Factors of Thinking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sequence of unit within the science course</td>
<td>Factors that Involve Both Affordances and Limitations</td>
</tr>
<tr>
<td></td>
<td>o Station rotations</td>
</tr>
<tr>
<td></td>
<td>o Drawing on sample units for activities and ideas</td>
</tr>
<tr>
<td></td>
<td>o Consistent use of language provided in the workshops</td>
</tr>
<tr>
<td></td>
<td>o Teacher gauging appropriate levels of cognitive demand</td>
</tr>
</tbody>
</table>

**Station rotations.** A central planning factor emphasized in each of the units and CoRes was the consideration of ensuring that each student be provided with at least two opportunities to operate the controls on the SEM. The summer course instructors strongly recommended rotating the laboratory stations with every-20-minutes rotations, although they did provide examples of alternative methods to structure stations. Teachers reported in their call-out reflections and in interviews that the 20-minute rotation period worked better for the smaller classes, where there was a grace period if students did not finish at the SEM in time. In classes with fewer than 30 students, teachers communicated in their call-out reflections and classroom observations confirmed that everyone was able to get up to three, 20-minute rotations on the SEM. In the case of the larger classes, teachers said in their call-out reflections and interviews that they felt the need to be very strict about the time-limit and provide only one or two, 20-minute rotations, which turned out to be difficult for many students. As one teacher related during the focus group:

The time that the students were allowed to spend with the SEM was super small; really you spend 10 minutes just telling them how the buttons work and then they get to click around for 10 minutes and then you’re like "take a picture, take a
picture, go!” and then, well I feel that that is the whole point of the whole thing is
to get their hands on that equipment and if you’re not doing that, well than, what’s
the point? All the rotations except for one they were either taking pictures with
the digital camera and drawing the image or using one of the dissecting
microscopes and taking pictures with that one, but they were really doing one
thing right after another so it was pretty quick. And with 10 minutes, I could get
them started on it, load it in about the first 3 minutes, and show them how to use
the controls in about 2 minutes which gave them about 5 minutes to play around.
It just wasn’t enough time for students to really get engaged.

During the interview teaches said that in some cases, students simply stayed on
the SEM longer than scheduled; thus only two instead of three groups accessed the SEM
per day. Teachers reported in their call-outs and during interviews and the focus group
that the problem created by time limitations were worse in classes of 30 or more students
where it became necessary for the teacher to be increasingly directive with students to
help them quickly move through the process so as to get the next group on the SEM.
Teachers noted that the 20-minute rotation with large classes radically shifted the way
they taught science as inquiry. In fact, during an interview one teacher questioned
whether or not the unit was an authentic inquiry process because she had become
increasingly directive as time ran out for students to work with the SEM.

**Drawing on sample units.** Because teachers were expected to begin planning
their unit on the third day of the summer workshop and had very little time to experiment
with the SEM and Leica on their own, instructors asked the workshop participants to
draw from available sample unit-plans posted on the course website and those listed as
links to the course website (e.g., Nano Sense; Nano.gov). Several teachers shared during
the workshop and in interviews that they literally used established lesson plans and most
teachers included in their units of instruction support materials provided by Project
NANO such as “station cards” that described the procedures at each station. Others wrote in their unit-plans and shared during their final workshop presentation that they drew liberally from the resources provided in the workshop and on the Project NANO websites (Google Group, Wiki and Media Fire) to scaffold learning experiences related to the learning objectives. During the workshop and follow-up interviews several teachers reported that because they had not had the opportunity to see the new district-wide science curriculum that they would be trained to use in September, they decided to limit the search for materials to those provided by teachers with experience teaching nanoscale science using the SEM.

**Consistent use of workshop language.** Similarly most teachers wrote in their call-out reflections that they literally used much of the same language modeled during the summer workshop, which limited them to activities that fit with the language. For example, it was noticed during classroom observations that teachers used terms they learned during the workshop to guide students through sample preparation such as “loading the stub”, “establishing quadrants on the stub using fiduciary marks” and “blowing off the sample” to ensure that the materials were “firmly stuck down.” Teachers reported in their call-out reflections and during interviews that they asked students to recite the list of things that can be loaded into the SEM using choral response patterns wherein students chanted at once “the sample must be dead, dry, non-magnetic and stuck down.” Each unit-plan included having every student who approached the SEM recite this list in order and then explain what the list meant before blowing off and loading a sample into the instrument. The group of students scheduled to be next on the SEM were
referred to as the “on-deck group” who were required to carefully listen and observe the sample loading and SEM operation procedures in preparation for reciting the procedures and using the SEM controls. Similarly, teachers maintained patterns such as asking students to write a description of the samples they placed in the SEM, note how the SEM worked and any other pertinent observations into a log posted next to the instrument.

Although this approach was intended to help students to remember the protocols and the reasons for the protocols, the strict adherence to repeatedly using the same terms to describe the procedures and protocols may have cause some students to get bored or based their actions on rote memorization rather than deep conceptual understanding of the procedures. Thus teachers shared during classroom observations, in the focus group and in their call-outs that the language tools meant to serve as affordances for learning, may have limited their own sense of how to use language to reinforce ideas and ensure that students thought about the procedures in way that would enable them to be able to transfer procedural knowledge for use with other microscopes.

**Gauging cognitive demand.** Teachers drew upon their metastrategic thinking to determine the appropriate level of cognitive demand to include in the unit largely based upon their own experience with understanding how to use the various SEM functions. A middle-level teacher expressed during an interview that, “It wasn't until I'd worked with dozens of stubs that I had an idea of proper size and what scans well, what doesn't scan well and how to use all the controls. It’s just that the first time using the equipment involves a huge learning curve.” Perhaps due to the limited duration of the summer workshop, it was observed that if groups of teachers struggled with technology in some
sense during the summer workshop, they were likely to either avoid this problem by
writing that function out of the unit or to specifically ask for coaching to overcome this
issue. In some cases teachers shared in their CoRe, call-out reflections and interviews that
they drew upon their own inquiry experience to redesign an existing unit to fit the needs
of a particular group of students (ex. credit recovery groups, low ability level grouping
and high-ability grouping).

In the case of the advanced placement science courses, teachers reported in
interviews and conversations following classroom observations that they purposefully left
out particularly difficult functions of the SEM in the unit because they felt that added
technical challenges and appropriate problem solving opportunities for these groups of
students. In the case of credit recovery groups, some teachers wrote in their CoRe tables
and call-out reflections that they needed to include only the controls that students were
most likely to be successful with because they had enough challenges with understanding
the content and did not need the additional challenge of figuring out how to use and
understand potentially confusing SEM functions such as the topo A and B views.

Teachers reported during the summer workshop and interviews that they also
considered strategies that might encourage students to design studies suitable as science
fair projects. Participants reported that they planned to make themselves available to
teach students more advanced ideas on the SEM and how to operate the controls if they
decided they wanted to use the instrument for a science fair project. Indeed students did
avail themselves to this opportunity to, according to teachers “play with the SEM”
outside of class time as an extension.
This concludes the description of teachers metasategic thinking developed from the data. Next, I describe forms of PCK teachers used and built to negotiate the inclusion of novel science and technology into the curriculum.

**Forms of Pedagogical Content Knowledge (PCK)**

This section of Chapter Four presents forms of PCK teachers drew upon to design and implement their unit(s). As stated in Chapter One, I maintain that teachers use metasategic thinking to inform their choices from their wealth of PCK to suit the needs of particular learners. Recall that Shulman (1986) described PCK as a teacher’s knowledge of the dimensions of subject matter for teaching using the most effective means of “representing and formulating the subject in a way that is comprehensible to others [and] understanding what about the subject matter makes it easy or difficult for students to understand” (p. 9). Shulman acknowledged that there is not one-best way or best activity to teach topics, but that teachers develop a “veritable armamentarium” (Shulman, 1998, p. 9) of representations some of which are derived from their own experiences as a teacher and others from research. The forms of PCK exhibited by participants in this study were: knowledge of science content, knowledge of instructional strategies, knowledge of curriculum, knowledge of student thinking, and knowledge of assessment as depicted in Figure 12.
This section of Chapter Four informs the research question, *how do teacher participants in the 2012 Project Nanoscience and Nanotechnology Outreach (NANO) program negotiate the inclusion of novel science and novel technology into the science curriculum?* Teachers applied their PCK to negotiate how to structure the unit and to inform their choices of instructional strategies used to facilitate the development of students’ scientific content knowledge and skills, including skills associated with higher order thinking. As mentioned in Chapter Three, teachers initially worked in groups or pairs to develop their units of instruction and then most teachers further revised their unit after the workshop to tailor lessons to meet specific developmental needs of their students and then submitted this refined version to the researcher for analysis. Because two groups of teachers chose to submit one unit they developed together during the workshop and
one teacher submitted two different units, the total number of units of instruction submitted by the secondary level members of the 2012 Project NANO cohort was 21.

Structural elements were described by secondary in-service teachers are: structure of classroom organization, use of adult volunteers in the classroom and ideas for how to solve technical issues related the scientific instruments. The instructional strategies they described are: scientific inquiry, student assessment and differentiation of instruction.

Table 11 depicts forms of PCK described by teacher participants. The table has three columns. The first column presents elements of the units of instruction. The second column presents categories of teachers' PC and the right-side column is a list of forms of PCK related to each of the categories of teachers' thinking listed in the center column. This third column was developed based on an assessment of the form of PCK teachers explicitly expressed verbally or in writing and the conceptual connections they described between the forms of PCK they drew upon to develop their rationales for how to teach particular topics.

It is important to note that the data presented in Table 11 was provided by teachers in response to questions that enabled an exploration of what teachers know about the content, instructional strategies, curriculum and assessment and, ultimately, knowledge of student thinking in relationship to how they learn particular topics. The data provided in the following table does not simply capture how teachers teach particular topics but rather this data describes various facets of their PCK that informed their rationales for how to teach particular topics in science and engineering.
### Table 11

**Forms of PCK**

<table>
<thead>
<tr>
<th>Elements of Units</th>
<th>Categories of Thinking</th>
<th>Forms of PCK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure of classroom organization</td>
<td>Activity Stations</td>
<td>Knowledge of instructional strategies</td>
</tr>
<tr>
<td></td>
<td>o Ten to 12 activity stations (Middle-level and High School)</td>
<td>Knowledge of curriculum</td>
</tr>
<tr>
<td></td>
<td>o Two stations per day (Middle-level)</td>
<td>Knowledge of content</td>
</tr>
<tr>
<td></td>
<td>o Dual stations (Middle-level)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>o The entire class completing one station per day as an whole group over a 2-week period (Middle-level)</td>
<td></td>
</tr>
<tr>
<td>Organization of Laboratory Groups</td>
<td></td>
<td>Knowledge of student thinking</td>
</tr>
<tr>
<td></td>
<td>o Teacher assigned students to small groups of 3-4 students each</td>
<td>Knowledge of instructional strategies</td>
</tr>
<tr>
<td></td>
<td>o Students selected groups of 4-5 students</td>
<td></td>
</tr>
<tr>
<td></td>
<td>o Teacher split the entire class into two large groups</td>
<td></td>
</tr>
<tr>
<td>Adult volunteers</td>
<td>Ways in Which Teachers Involved Adult Volunteers</td>
<td>Knowledge of instructional strategies</td>
</tr>
<tr>
<td></td>
<td>o Five middle-level teachers involved adult volunteers</td>
<td>Knowledge of the curriculum</td>
</tr>
<tr>
<td></td>
<td>o High School teachers did not involve adult volunteers</td>
<td></td>
</tr>
<tr>
<td>Technical problems and solutions</td>
<td>Technical Problems and Solutions with Microscopes</td>
<td>Knowledge of science content</td>
</tr>
<tr>
<td></td>
<td>o Image capture function</td>
<td></td>
</tr>
<tr>
<td></td>
<td>o Quality of images</td>
<td></td>
</tr>
<tr>
<td></td>
<td>o Saving and transferring images</td>
<td></td>
</tr>
<tr>
<td></td>
<td>o Sample preparation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>o Scaffolding preparation to work with microscopes</td>
<td></td>
</tr>
<tr>
<td>Scientific Inquiry</td>
<td>Science Inquiry Continuum</td>
<td>Knowledge of instructional strategies</td>
</tr>
<tr>
<td></td>
<td>o Highly directive inquiry process</td>
<td>Knowledge of student thinking</td>
</tr>
<tr>
<td></td>
<td>o Guided inquiry process</td>
<td></td>
</tr>
<tr>
<td></td>
<td>o Open-ended inquiry process</td>
<td></td>
</tr>
<tr>
<td>Student assessment</td>
<td>Forms of Assessment</td>
<td>Knowledge of assessment</td>
</tr>
<tr>
<td>--------------------</td>
<td>---------------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td></td>
<td>o Summative assessments of final products</td>
<td></td>
</tr>
<tr>
<td></td>
<td>o Formative assessment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Discussion groups with guiding questions</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Periodically checking students’ work</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Working with student team managers to check student progress and adjust instruction</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Differentiations strategies</th>
<th>Forms of Differentiation</th>
<th>Knowledge of assessment</th>
<th>Knowledge of instructional strategies</th>
<th>Knowledge of student thinking</th>
<th>Knowledge of science content</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>o Activities with a variety of learning modalities</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>o Activities that appeal to different learning styles</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>o Responses to formative assessments</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Forms of PCK.** I begin by describing the forms of PCK in the column found on the right-hand side of Table 11 which I have depicted once more in Table 12 below. Notice that all five forms of PCK are found in this study. However, it is interesting to note that knowledge of instructional strategies and knowledge of student thinking comes up as the most frequently described forms of PCK employed by the teachers in this study. Indeed, knowledge of instructional strategies appears all six of the categories of thinking listed in the table and knowledge of student thinking appears in four of the six categories of thinking. On the other hand, knowledge of the curriculum, knowledge of assessment and knowledge of the content comes up only twice respectively out of the six categories.
It is intriguing to note that the forms of PCK that come up most frequently could provide clues as to the entry points on a learning progression that these teachers experienced as they drew upon their PCK to negotiate the inclusion of nanoscale science and technology into the curriculum for the first time. Although Project NANO purposely provides supports to encourage teachers to begin the unit planning process by foregrounding knowledge of content, knowledge of student thinking and knowledge of assessment, it appears that it may be possible that teachers remained focused on their knowledge of instructional strategies and their knowledge of student thinking as primary concerns throughout the planning, implementation and reflection cycle of the unit. That said, although teachers shared their PCK related to these two forms of PCK more frequently than other forms of PCK, the fact that teachers were able to more frequently articulate their knowledge of instructional strategies and student thinking does not necessarily mean that teachers drew more or less on one form of PCK than another. It may simply be the case that the methodologies used in this study to elicit teachers thinking were more sensitive to picking up knowledge of instructional strategies and knowledge of student thinking than other forms of knowledge. Thus the frequency of

<table>
<thead>
<tr>
<th>Knowledge of Instructional Strategies</th>
<th>Knowledge of Student Thinking</th>
<th>Knowledge of Curriculum</th>
<th>Knowledge of Science Content</th>
<th>Knowledge of Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 12

*Forms of PCK Used Related to the Six Categories of Thinking*
how many of the forms of PCK appeared in each of the categories may be less important than one may at first assume.

I posit that the more important story to be told here about the forms of PCK teachers drew and built upon to negotiate the inclusion of nanoscale science and technology into the curriculum is found in the descriptions provided in the following sections. I begin with the category of thinking related to how teachers thought about the use of activity stations in their units of instruction.

**Activity Stations.** Here, I report on the forms of PCK related to how teachers chose to organize the structure of their classroom. I begin by describing how they organized activities beginning with Table 13 which depicts thematic patterns of PCK and forms of PCK related to the category that relates to the structure of classroom organization.

**Table 13**

*Forms of PCK Used to Determine the Design of Activity Stations*

<table>
<thead>
<tr>
<th>Elements of Units</th>
<th>Categories of Thinking</th>
<th>Forms of PCK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure of classroom organization</td>
<td>Activity Stations</td>
<td>Knowledge of instructional strategies</td>
</tr>
<tr>
<td></td>
<td>o Ten to 12 activity stations (Middle-level and High School)</td>
<td>Knowledge of curriculum</td>
</tr>
<tr>
<td></td>
<td>o Two stations per day (Middle-level)</td>
<td>Knowledge of content</td>
</tr>
<tr>
<td></td>
<td>o Dual stations (Middle-level)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>o The entire class completing one station per day as a whole group over a 2-week period (Middle-level)</td>
<td></td>
</tr>
</tbody>
</table>
All of the units of instruction involved activity stations in some form, although teachers applied their PCK in different ways to approach the role of the stations and how students interacted with them. Teachers drew on their knowledge of instructional strategies, knowledge of curriculum and knowledge of content and of student thinking to plan how to organize student activities.

Analysis of the units of instruction and CoRe tables revealed that teachers designed four different approaches to how students interacted with activities in the unit. The majority of the teachers (N = 18) employed a strategy known as cyclical rotation through stations. Teachers designed 9-12 activity stations (see case-by-case studies in Appendices A through D for examples of stations) that students rotated through over the course of one or two weeks. In three cases, teachers began the unit prior to the arrival of the Project NANO toolkit in the classroom with station activities that prepared students for the use of the microscopes, thus their unit was three weeks long rather than the more typical two-week long unit. Students typically rotated through two to three stations per class period. The duration of each microscope station was 20 minutes long and some of the stations involved more than one activity. Student lab groups each had two rotations on the SEM with the goal of the first being to generally become accustomed to the instrument and controls and to capture images. Students then did a second rotation which provided them with the chance to capture higher quality images demonstrating characteristics in samples that best exemplify scientific claims they chose to make in their final report and presentation.
Although the learning objectives in each of their units were very different, two sets of middle-level teachers partnered together to refine their thinking about how to negotiate the inclusion of technology into the curriculum. During the focus group discussion they reported that they conducted peer-observations in one another’s classroom in units taught prior to the Project NANO unit to gather ideas for how to organize stations in different inquiry-based units. These teachers reported that they discussed and refined their rationale for how to structure activities to best facilitate the development of students’ higher order thinking skills and also practiced how to use the SEM.

One of these teachers also conducted multiple peer-observations periodically throughout a more experienced teacher’s Project NANO unit and developed new PCK for how to organize his own stations in their nanoscale unit. During the focus group this less experienced teacher shared:

One thing that was very helpful, I actually went and watched [my colleague] a couple of times because I was really nervous. I had sleepless nights, literally, sleepless nights. That [peer-observation and discussion] really put me to rest, especially for people going in this late in winter, because it was just so long ago [that I learned how to use the SEM in the summer], and I was really worried I was just going to forget all this stuff, so it was really helpful to take a couple of hours and go see another teacher teach it and see what stations look like, especially at middle-level and to just remind myself all the nuances of the SEM. And I was able to get some feedback, some wisdom from [my colleague] that I was able to kind of think ahead...

During the workshop two sets of middle-level teachers said that they decided that the 20-minute rotation through stations approach was inappropriate for the middle-level learners in their classes, especially because they valued “providing enough time for
students to play with the SEM before getting down to business and capturing images for their report.” The teachers said that this “play time” was essential so that students could have a chance to explore features of various materials and discuss the characteristics they observed. Based on this decision, these teachers each designed two, 45-minute stations per day for the entire class of students for a 90-minute period. The cooperating teacher selected two small groups of three to four students per day to work with the two microscopes for 45 minutes each while his student teacher managed the rest of the class at the other stations.

To accommodate for his large class sizes of 42 students, a middle-level teacher said in his CoRe table and during the interview that he chose to design what he referred to as “paired stations.” In other words, he set up two of each station, each with the same activity or set of activities. While one group of four students worked with the SEM and Leica at one station, another group of four students was on-deck watching and listening to the group working with the microscopes in preparation for their turn. The rest of the class was assigned into groups of four students by the teacher to complete activities at two stations per day. This way eight students at a time worked on the same activities set up on two different tables. Thus, including the microscope station, the teacher only needed to check in on three unique stations per class rather than attempting to manage students at nine to 12 different activity stations.

Finally, one teacher wrote in her unit of instruction, CoRe and call-outs that she chose not to use the stations approach at all, but rather had the entire class complete one activity per day over a 2-week period. This high school biology teacher wrote in her call-
out reflections that she did it this way so that she could spend half of the class period providing background information, assisting students in decoding the instructions for the lab activity and circulating around the room to ensure that everyone was on-task and knew what to do. She spent the second half of the period taking a small number of students to the SEM to have a turn examining materials that she provided to explore questions that she framed for them. At the end of each period, she worked with the entire class to facilitate discussions that assisted students in connecting the concepts addressed in the activities to the learning objectives of the unit.

**Grouping of Students.** Table 14 presents a description of how teachers drew and built upon their PCK related to knowledge of instructional strategies, knowledge of curriculum and knowledge of content and of student thinking to figure out how to group students for different activities based on what they knew about the science content, curriculum and student thinking.

**Table 14**

*Forms of PCK Used to Decide How to Group Students*

<table>
<thead>
<tr>
<th>Elements of Units</th>
<th>Categories of Thinking</th>
<th>Forms of PCK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure of classroom organization</td>
<td>Organization of Laboratory Groups</td>
<td>Knowledge of student thinking</td>
</tr>
<tr>
<td>o Teacher assigned students to small groups of 3-4 students each</td>
<td>Knowledge of instructional strategies</td>
<td></td>
</tr>
<tr>
<td>o Students selected groups of 4-5 students</td>
<td></td>
<td></td>
</tr>
<tr>
<td>o Teacher split the entire class into two large groups</td>
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<td></td>
</tr>
</tbody>
</table>
Examples of how teachers grouped students are:

- **Whole group activities**
  - Receipt of knowledge from teacher (direct instruction)
  - Discussion groups (with an emphasis on looping discussions)
  - Sample preparation
  - Student presentations

- **Small group activities**
  - Nanoscale science content related activities (videos, games, readings, and worksheets)
  - Microscope stations
  - Creating reports

All of the teachers who organized their students into small lab groups (N = 22) provided two reasons for why they chose this format. The first and most frequently mentioned reason provided in the CoRe tables, call-out reflections, focus group and interviews is that they followed the model provided at the summer workshop. As one teacher emphasized during an interview, “Yeah, they definitely wanted us to do it a certain way and that’s how we did it…with the stations and all of that…” The second reason mentioned by each teacher relates to student thinking, captured in this representative quotation from a middle-level teacher during the focus group is that, “Small groups of three to four allow for speed in work but also collaborative work and discussion.”
Twenty of the teachers grouped students for sample preparation as one of many stations that students rotated through. Teachers wrote in their unit-plans that they started off the first rotation leaving out the SEM and Leica on the first day so that students would have a chance to prepare and mount their samples first and avoid wasting any of their microscope time.

In his call-out reflections and during an interview, one teacher described how he approached sample preparation differently than the rest of the participants in the study:

They [students] did the Leica [microscope slide preparation] and the [SEM sample] stubs together as one station and I had everyone in the class split up in groups of two; the group that finished the first stubs, they were going to be the first driver [on the microscope controls] for the next time, so when they were done [preparing slides and stubs], which wouldn't take the entire 45 minutes, they would actually rotate onto the SEM.

Two middle-level and one high school teacher said during the workshop and in interviews that they chose not to include sample preparation as a station, but rather involved the entire class in preparing and mounting samples. Students in these classes took an entire class period to prepare slides and stubs and check each other’s work to ensure that all samples fit the criteria for each microscope and were correctly mounted on the sample slide or stub. These teachers explained that their rationales were based on their knowledge of student thinking and as a time-efficient approach as demonstrated by the following quotation:

So I did know that middle school students can prepare samples; they prepped their own stubs. They did the [Leica slides] and the [SEM] stubs together as one station and I had everyone in the class split up in groups of two, the group that finished the first tabs, they were going to be the first driver in the photo taker for the next time, so when they were done with the tabs, which wouldn't take the entire 45 minutes, they would actually rotate into the SEM station.
Teachers who completed the implementation cycle by the end of the data collection period shared their ideas in call-out reflections and in interviews their PCK for how they approached forming small laboratory groups of students. It is interesting to note in the unit-plans that all of the experienced teachers and one novice teacher assigned students to small groups. When asked about this decision at the summer workshop and during interviews teachers said that assigning groups of students rather than allowing students to form the own groups provided the teacher with more control over the student groups because they could balance various learning aptitudes and personalities within each group. A high school teachers’ comment during an interview well represents the PCK that characterized the rationales of all the teachers who assigned students to groups:

One way that I tried to address differentiating the different levels in terms of the abilities of students in biology is that I picked their groups so that I could identify who I thought would be a team leader in each group and then have students who were really strong in science and students that maybe were a little timid or unsure of their skills grouped together. So that enabled me, right from the start, to have more control. I have their [written] reflections of ‘how did it go in your group’ [from the exit tickets] that then helped me to support the team leaders to manage the groups. So how do I differentiate? How do I make sure that all of the learning styles and needs are met? One way to do that is to have more control over the groups.

As was the case for this teacher, several veteran teachers and one novice teacher said during interviews and in call-out reflections that they selected and prepared student “team managers” to facilitate their own group. Teachers' PCK related to student thinking guided their decisions as to which students to select as team leaders, as exemplified in the following quotation:
I didn’t necessarily select the ‘smartest students’ to act as team managers, I selected creative and charismatic kids whom I really felt would benefit from a leadership experience and do a good job with their team, you know keep them going, keep them on task and moving forward.

Teachers shared in call-outs, during interviews and classroom observations that they prepared team managers in the weeks before the unit by pre-teaching major scientific and engineer concepts to be covered in the unit. They met with student team leaders afterschool on the day that the SEM and Leica arrived to show the students how the instruments work and discussed procedures and language they would be expected to use on a consistent basis. During a classroom observation one teacher said that he also gave the team managers readings that describe facilitation strategies and then met outside of class to role-play scenarios using these strategies.

Most of the teachers reported in their call-outs that they instituted a sign-up sheet for the SEM so that the lab groups could track when their group would be the on-deck observing the group on the SEM rather than the teacher needing to keep track of the rotations. Teachers who did not do this reported in the interviews that they experienced a high level of stress as they attempted to manage station rotations. As one teacher who forgot to use the sign-up sheet modeled in the summer workshop shared in an interview, “I didn’t use the sign-up sheet for stations so I had to keep track in my mind which meant that it was more management for me and stress.” Teachers who did use the sign-up sheet and the on-deck approach related in their call-outs, in interviews and the focus group that students said that they felt like they knew what they needed to do and when, were empowered to think ahead and anticipate tasks and thus, were able to efficiently stay on
task throughout most or all of the inquiry cycle. As one high school teacher who used the sign-in sheet and on-deck method related during an interview:

They [students] didn’t waste any time rotating, which is great since they have so little time at each station. It’s good that they watched first when they were on-deck, so they knew what to do and were able to get right on [the SEM] and run with it. Once the kids rotated onto the SEM, they picked up the controls and ran with them really fast. So we moved past the ‘how do we use this thing?’ stage really fast; students were able to get down to business checking out samples at different scale and snapping images they could use for their inquiry.

**Adult volunteers.** Another form of PCK used by teachers relates to the topic of adult volunteers. Throughout the summer workshops, the co-instructors emphasized the importance of recruiting adult volunteers to assist with the unit. They also provided numerous examples both verbally and in writing of the roles volunteers have played in past Project NANO units and how to prepare volunteers for those roles. According to the units of instruction and call-out reflections, only one high school level teacher chose to incorporate a volunteer in his classroom, although one second-year chemistry teacher (see Paul’s case in Appendix A) related during an interview that he taught his unit “with no volunteers so I'm the only one handling the whole room, so there’s the reason why it turned into this sort of management nightmare for me.” Table 15 depicts forms of teachers’ PCK related to the involvement of adult volunteers in their nanoscale unit of instruction.
Table 15

*Forms of PCK Related to Adult Volunteers*

<table>
<thead>
<tr>
<th>Elements of Units</th>
<th>Categories of Thinking</th>
<th>Forms of PCK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adult Volunteers</td>
<td>Ways in Which Teachers Involved Adult Volunteers</td>
<td>Knowledge of instructional strategies</td>
</tr>
<tr>
<td></td>
<td>o Five middle-level teachers involved adult volunteers</td>
<td>Knowledge of the curriculum</td>
</tr>
<tr>
<td></td>
<td>o Only one high school teacher involved an adult volunteer</td>
<td></td>
</tr>
</tbody>
</table>

The six of 11 middle-level teachers who chose to involve volunteers drew upon their knowledge of instructional strategies and knowledge of student thinking to figure out how to draw upon adult support throughout the unit. These six teachers took a variety of approaches to preparing and managing volunteers. One of these teachers wrote in her call-out reflection and shared during an interview that she trained her parent volunteers after-school a week before the unit began. She assigned specific roles for each adult volunteer and modeled how to perform each role prior to the beginning of the unit. During this training, she provided each adult with written descriptions of what each of their roles in the classroom would be throughout their volunteer experience. This middle-level teacher also reported that during the training she provided her volunteers with content-based readings, web-links to informational videos on the content, an outline of the instructional plan and a schedule of activities. She requested of her volunteers that they arrive in class 10-minutes early to review their roles and be ready to help when the students arrived. She reported during an interview that the six to eight volunteers per day
were very helpful and did not require that she manage their activity beyond the initial check-in at the beginning of each class period.

The one high school teacher who involved an adult volunteer drew on the support of a retired biology teacher who had worked in that school for over 35 years. In fact, several students reported that this teacher had taught their parents when they were in school and that this was someone they felt very comfortable working with in class because he volunteered nearly every day in their biology classes all year. This volunteer co-planned the nanoscale science unit with the teacher during the revision phase of the planning and took responsibility for supporting students on all of the activity stations except for the SEM station. The volunteer told the researcher that he was very comfortable facilitating the students at each station in part because he was very comfortable and familiar with the content and curriculum and in part because he had personally done each of the activities at the stations himself prior to the beginning of the unit and debriefed with the teacher how to anticipate student responses to each activity. After the initial check-in and warm-up at the beginning of each class, the classroom teacher was responsible for supporting students on the SEM which was located in a supply room off of the main classroom, where he would remain for most of each period throughout the unit. Each day after class, the volunteer and teacher checked in on student progress and refined their strategies for how to support particular students and groups of student the next day.

A middle-level teacher who had four to six adult volunteer nearly every day of the unit shared during an interview that she did not provide clear volunteer roles, prepared
adults during the passing period between classes and felt unsure about how to operate the
Leica let alone teach a parent. Another middle-level teacher shared during an interview
that he also quickly prepared volunteers and did not provide them with background
content or specific roles. He related “I trained volunteers, they are very busy people, it’s
kind of hard to train them...that’s very difficult actually, it’s really hard to train them and
expect them to turn around and start teaching right away.” Although one mother
volunteered every day throughout the unit, there were three to four new parent volunteers
in the classroom each day, none of whom were scientifically trained. Thus the teacher
wrote in her call-outs and said in an interview that the presence of volunteers in the
classroom added to her stress level. Both the adults and the students had a less successful
experience compared to the teachers who prepared a consistent set of volunteers or one
volunteer who helped throughout the unit.

In comparison to reports from other teachers who had adult support in the
classroom, those teachers who had the support of student teachers reported in their call-
out reflections and in interviews a much higher level of success in collaborating to
facilitate student inquiry than those teachers who drew upon the support of parent-
volunteers. In fact, the scientifically trained student teachers were reported by their
collaborating teachers to be instrumental to the success of open inquiry lessons, in large
part because they brought with them PCK for how to guide and encourage students using
scientific instruments to explore nanoscale concepts within the context of an inquiry-
based experience.
The cooperating teachers communicated in the focus group that each of their student teachers who had also taken the Project NANO summer workshop worked in close partnership as a co-developer and co-instructor. One teacher reported during the focus group that his student teacher was invaluable to the success of the unit, “because he was fully equipped with the scientific content knowledge to support students and he was in a receptive place to be mentored to learn teaching skills [and] because he fully understood the learning goals and strategies and specific language we had agreed to use when we planned the unit together.” Another middle-level teacher declared:

I had a Noyce Scholar who came in, and it was invaluable. I mean I just can't imagine running it, especially in the first year, I just can't image running it without it [trained support]…that was huge. The kids were just really apprehensive, you know they have limited time and you really have to push them to push that machine to its limits cause if they didn't it would be like driving a car for the first time, if you are really kind of soft on it, they wouldn't get that experience and that pushing to get the images, that was really helpful to ensure that they captured images that could actually be useful to them [in the scientific inquiry process].

**Technical problems and solutions**. Throughout the summer workshop and implementation of the unit, teachers negotiated a variety of technical issues. These issues were: remembering how to use the SEM, figuring out the best place to situate the SEM and Leica in the classroom, figuring out the image capture function on the Leica microscope, acquiring quality images on both microscopes, saving and transferring images and sample preparation. The following table 16 shows forms of teachers' PCK related to how they negotiated technical problems they encountered and solutions they developed to overcome technical barriers.
Table 16

Form of PCK Related to Technical Problems and Solutions

<table>
<thead>
<tr>
<th>Elements of Units</th>
<th>Categories of Thinking</th>
<th>Forms of PCK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical problems and solutions</td>
<td>Problems &amp; Solutions with Microscopes</td>
<td>Knowledge of science content</td>
</tr>
<tr>
<td></td>
<td>o Image capture function</td>
<td>Knowledge of instructional strategies</td>
</tr>
<tr>
<td></td>
<td>o Quality of images</td>
<td></td>
</tr>
<tr>
<td></td>
<td>o Saving and transferring images</td>
<td></td>
</tr>
<tr>
<td></td>
<td>o Sample preparation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>o Scaffolding preparation to work with microscopes</td>
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</table>

Each teacher in the program was assigned one of the summer workshop facilitators as a coach during the academic year. Two weeks prior to receiving the Project NANO toolkit, the coach contacted the teacher to schedule time to review the unit and problem-solve technical issues. In each case, the coach met with the teachers to review the functions of each microscope, discuss the technical limitations of each instrument and talk about specific language used to facilitate students using the microscopes. During an interview, one teacher underscored her coach’s support as crucial to relieving her anxiety prior to beginning the unit:

The coaching on how to use it was obviously useful. When I got the equipment in the room, I had forgotten a lot of that, and [my coach] actually came by in the morning for quick refresher for me, which was really super, and as he was showing me, it had been so long that I was afraid that I wasn’t going to remember, so that was nice. I was like oh, yeah I remember now. And then someone standing behind me saying focus here, do this, do that, you know you can’t really do that with something that complicated without someone being there to do that…

On the day that the Project NANO toolkit arrived at the school, the coach met with each teacher to also strategize where to place each of the stations in the classroom,
especially where to set up the SEM and Leica stations. Constraints that coaches and teachers considered were: placing each instrument on a stable surface (not in a fume hood) near a reliable electrical socket in the same room as the other stations if possible, placing the instruments near enough to one another to accommodate teachers supporting students at both microscope stations and placing activity stations with a higher level of cognitive demand closer to the SEM and Leica.

According to information shared during interviews, classroom observations and in call-out reflections, several of the schools involved in the program are housed in buildings constructed between 1915 and the late 1960s. Many of the older electrical sockets were loose and unsuitable for plugging in the SEM that needs to be recalibrated and can take up to 12 hours to pump down and recalculate each time it loses power. Thus, teachers’ choices of where to place each microscope were limited by the availability of quality electrical sockets and sturdy benches or tables.

Two of the eight school districts have strict internet firewalls that prevent students from logging onto the internet to conduct Google searches and to access videos on YouTube and other sites where the Powers of Ten videos and web based station activities are found. Thus, teachers wrote in their CoRe tables and shared during discussions in the workshops that they anticipated that they would need to re-enter their own password into computers each time the computers went to sleep. This problem was important because as one teacher put it during a classroom observation, “it doesn’t take much for freshman to get off task, so having to wait for me to come enter my password doesn’t just waste time, it threatens kids’ momentum and focus.” Thus, the laptop computers needed to be placed
nearby the SEM and Leica where the teacher was stationed, placing an even greater demand on the electrical sockets in classrooms where it is not unusual for there to be only one or two outlets in the entire room with surge-protector power strips plugged into them.

In some cases, teachers said in their unit-plans and CoRes that they had access to two different carts with class sets of laptop computers so they were able to charge one set of laptops while the other cart was in use. During the workshop teachers shared that in order to do this, they needed to reserve both carts and then argue the need for this strategy when other teachers wanted to know why they could not access any of the carts for many of the class periods for up to three-weeks. Thus it became apparent early on that other teachers in their building needed to be made aware of the project. One teacher articulated during an interview that,

It was good that you guys gave us that memorandum of understanding about Project NANO to share with our colleagues; otherwise they wouldn’t have understood why we needed to have so many resources. Plus, the Math teachers and English teachers and even our Art teacher figured out how they could build on what kids learned in my class. So what started out as a means to avoid arguments, turned into some really productive collaboration.

The coaches and I observed that although each teacher was required to pass a practical exam to demonstrate that they knew how to use each microscope, those teachers who had allowed others in their group to manipulate the instruments throughout the majority of the summer workshop inquiry experience had difficulty remembering how to use the instruments. Upon realizing this early in the academic year, the coaches and researcher identified teachers who had less time on the instruments at the summer workshop or seemed to lack confidence or proficiency using either of the microscopes.
The coaches then scheduled to assist on the first day of the unit in each of these teachers' classrooms to model how to use the instruments with students and how to facilitate others as they learned the functions of each microscope. These teachers reported during interviews and in their call-out reflections that this extra assistance was invaluable in terms of increasing their confidence levels, reducing anxiety and providing as one interviewee put it “little tips and tricks” useful for working with students and adult volunteers on each microscope.

This language of tips and tricks was concerning to the coaches (and the researcher) because we worried that teachers were not understanding the underlying theory behind instructional strategies modeled by the coach. For example, an important guiding learning theory for how the coaches facilitated students on the SEM is social constructivism. Rather than simply pointing out things to notice in a specimen viewed under a microscope, the coach asked the group of students discussion questions meant to stimulate lab groups to think and talk about the characteristics in the images that relate to their research question when looking at the SEM images on a computer screen. Thus, the coaches intentionally modeled instructional strategies that were meant to engage students in using and developing higher order thinking skills using the microscope.

Two middle-level teachers reported during an interview that one visit from their coach on the first day of the unit was not enough and that they continued to struggle with remembering not only how to use the microscopes, but also how to describe the steps to others. In these cases, teachers expressed that they wished that they had more time with
their coach because they continued to struggle with understanding and describing the overall concept of the nanoscale until at least a week into the unit of instruction.

Another idea shared by teachers in their call-out reflections and during interviews was that students had difficulty with capturing and transferring images with the Leica microscope, saying that:

The Leica also had issues with the SD [secure digital] cards, there was a lot of issues of putting that [SD card] into the laptop and it wouldn't transfer the pictures or it would get full really easily…you would have to learn to delete someone else's pictures, so there were a lot of memory issues with the Leica and so some of my students ended up losing their pictures after they took them.

Another teacher shared his solution to this problem:

We had troubles getting that thing to take pictures with the card in, it’s really tricky, so we thought, there’s no way middle-level kids can get shots cause you push it and you wait. So I just hooked it [the Leica] up to the computer. There should be a mini-USB to a USB cord, I brought one from home. I set up folders on the desktop, it was awesome, it worked great, I never had a problem, with the computer system, it’s much more user friendly. So I really strongly recommend that this is implemented in the course for the next summer course.

During an interview teachers shared that students struggled with acquiring quality images on both microscopes. For example, just as the teachers experienced during the summer workshop, teachers reported that their students captured what they believed to be clear, well focused images with the Leica only to find when they viewed their images on the computer screen using the Image J software that the image clarity wasn’t as good as they thought it was. Thus, they needed to have another rotation on the Leica to learn how to capture clear images by using the microscope lens to focus rather than the camera lens. A high school physics teacher shared during an interview:
the only bummer is that the kids would be looking through the camera lens and
they wouldn’t be looking through the Leica lenses which you know, those are the
expensive lenses, the camera, it’s a $50 camera lens mounted on a microscope
with a $1,000 lens, so you really had to encourage them to look through the
[microscope] lens too because they were very different.

Teachers also negotiated problems with thumb drives used to capture and transfer
images from the SEM to a computer. In several of the schools, teachers reported in their
call-out reflections and in interviews that students consistently either forgot to bring
thumb drives, brought in pre-formatted thumb drives that did not work on the SEM or
students could not afford to purchase one. Teachers developed two solutions for this
problem, as one teacher indicated during an interview, “what we did is that we had three
thumb drives; we didn't have kids bring in any. So we had three thumb drives that
rotated, we named them one-two-three and we just rotated them through.” Teachers who
developed this solution suggested that this strategy be discussed at the next summer
workshop. They recommended that each of the thumb drives be on a lanyard so they are
easier to carry and less likely to be misplaced and that each thumb drive be numbered so
that the teacher can track where they each one is among the rotation of groups.

In three of the teachers’ classrooms, a folder on the desktop of a classroom
computer was assigned to each group. One teacher shared his PCK about student thinking
during an interview:

One of the stations was to go and get the Leica images off the computer with their
flash drive, download, go through the images decide what they throw away,
decide what they would keep, and then they would return the thumb drive to
rotate to the group that was on-deck waiting for their turn on the microscope.
Students would then upload what they considered to be their best images to space that the teacher purchased for $25 on the Media Fire website so that students could share images for discussion.

Throughout the call-out reflections and interviews, teachers spoke about their own process of becoming better microscopists in preparation to teach students how to use the SEM and Leica. One teacher’s summary echoed the sentiments of all of the teachers in the sub-group:

It wasn't until I'd worked with dozens of stubs that I had an idea of proper size [of samples to put in the SEM] and what’s scans well, what doesn't scan well and I don't know if you can get that in a one to two week course…it’s that first time using the equipment that it’s a huge learning curve, and then year two and year three you get that experience. It takes experience with it, so I don't know if there was anything you could have pre-taught me that would prepare me for it [laughs] cause it’s just a piece of equipment we have so little experience with. It’s going to be different for each person, what they will have troubles with, whether it’s the machine itself or imaging concepts.

Science inquiry. Teachers used a variety of approaches to structure the scientific inquiry process in their classes ranging from highly directive approaches to guided inquiry to open-ended inquiry. Here, I present Table 17 as an introduction to how teachers chose to situate their unit along this science inquiry continuum as described by Marshall et al., 2009,
Table 17

*Forms of PCK Related to Where Inquiry Units Fell on the Scientific Inquiry Continuum as Described by Marshall et al. (2009)*

<table>
<thead>
<tr>
<th>Elements of Units</th>
<th>Categories of Thinking</th>
<th>Forms of PCK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scientific Inquiry</td>
<td>Science Inquiry Continuum</td>
<td>Knowledge of instructional strategies</td>
</tr>
<tr>
<td></td>
<td>o Highly directive inquiry process</td>
<td>Knowledge of student thinking</td>
</tr>
<tr>
<td></td>
<td>o Guided inquiry process</td>
<td></td>
</tr>
<tr>
<td></td>
<td>o Open-ended inquiry process</td>
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</table>

Three middle-level teachers and one high school teacher designed units I characterized as being at the “developing inquiry” position on the science inquiry continuum described by Marshall et al. (2009) that ranges from pre-inquiry to exemplary inquiry. Two of the middle-level teachers and the high school teacher who designed a highly directive unit of instruction were novice teachers and one has taught sixth grade science for more than 15 years. These teacher-centered units were mostly prescriptive involving students in an investigation of a question or questions posed by the teacher rather than by the students. They each described their unit as an inquiry-based unit because students completed the cycle of investigating a question, building a body of evidence to support or refute a claim and defending an argument in their final written reports.

During an interview one middle-level described her rationale for this choice to design a “fairly step-by-step unit” based on her PCK related to what she understands about student thinking and instructional strategies:
Students at the middle school level often struggle with synthesizing information or ideas that don’t fit with their previous ideas. Collecting data is also dependent on student skills, which are still being developed. Students know that in the classroom, there usually is a “right” answer that they are trying to find, which dilutes the inquiry experience. It’s my job to provide them [students] with incremental experiences that guide them towards developing their understanding of the nature of science a step at a time beginning with proscriptive opportunities so that they will have the skills to work more independently later.

Teachers operating at the developing inquiry level selected materials to examine and provided students with the language they were to use to characterize each sample. During an interview one teacher described her knowledge of student thinking that informed her rationale, “Students need to practice putting their thoughts into words. They often can explain why they came to the conclusion they did, but have a difficult time writing it out.” According to the units of instruction, CoRe tables and interviews, these teachers prepared samples on stubs and slides themselves outside of class time, loaded samples into the SEM for the students and physically and verbally modeled how to use the functions of each instrument throughout the first 20-minute rotation on the SEM. One of these middle-level teachers also loaded the samples and operated the controls until the instrument was in the SEM mode for both the first and second group rotation. During an interview she said that she chose to do this “because I was freaked out that they might break the SEM, so I just got them to the place where they really couldn’t do anything to hurt it.” Each of these four teachers created fill-in-the-blank student work packets that required students to solve problems using defined protocols and provide one correct answer.
Each of the activities at the stations required students to think to the level of memorization and understanding using lower order thinking skills. There was very little difference in terms of the level of cognitive demand at each station with the exception of the Leica station where students needed to problem solve how to capture quality images without the support of the teacher or another adult. Students were not asked to argue or defend their claims with their peers, but rather to present their data in written form in a group science report that served as a summative assessment.

Little to no use of formative assessment was reported by this group of four teachers; in their call-out reflections and interviews each of these teachers claimed that given that they were “stuck” at the SEM, they were unable to use formative assessment strategies or to differentiate instruction. These teachers also said that they did not periodically check the student work packets but rather waited until the end of the unit to score the packets when they scored the final reports. These teachers shared during the focus group and one individual interview that they realized that waiting to check the student works packets at the end of the unit compromised their abilities to address students’ needs in a timely manner. Regardless of the frequency of how often these teachers checked the student packets, each student was graded individually, with the majority of the unit points assigned to sections of the work packets each student filled out individually.

Eighteen of the teachers designed their units of instruction as a guided inquiry process I characterized as being “proficient inquiry” on the inquiry continuum described by Marshall et al. (2009). In this case, teachers provided the learning objectives and big
ideas in nanoscale science that framed the inquiry process and used a variety of approaches to deliver foundational knowledge and skills necessary to conduct the inquiry. Some teachers wrote in their units and CoRes that they provided this foundational knowledge by asking students to make and record initial observations in preparation for small group or whole class discussions in response to guiding questions and some teachers presented content using a PowerPoint presentation first and then facilitated students on the microscopes by briefly modeling a function and then asking students to perform the function such as rastering samples in the optical mode, changing labels, switching to SEM mode and then using the focus and contrast controls. I noticed during classroom observations that students in the on-deck position were asked to recite the procedures as they witnessed them before they were allowed to blow off their stubs with the canned air to ensure samples were stuck down to the stub and then load samples into the SEM and manipulate the instrument controls.

Some teachers felt that it was essential to allow students to select their own samples to examine. One biology teacher emphasized during an interview:

I felt like I wanted to give my freshman students the freedom and flexibility and to encourage that academic autonomy, [as if speaking to a student] you need to find the biological connections, we are studying these range of topics and from that range of topics, you need to make some connections that are going to give you some higher level thinking skills by analyzing and categorizing samples.

Based upon teachers’ own experiences during the summer workshop with samples that either did not image well with the SEM or turned out to be unsuitable for the instrument, five teachers shared during an interview and in their call-out reflections that they provided a selection samples for students to choose from as back-up specimens. One
of these five teachers reported during the focus group, “I gave them a list of things that I could get for them and I said that if they want to look for something else they can.” In response to this comment during the focus group discussion, another teacher said that he did this too because he anticipated that students might bring in samples that either did not image well or may not provide suitable evidence to pursue their inquiry questions.

Other teachers wrote in their CoRe table that they decided to bring a selection for students to choose from rather than allowing students to bring in their own samples because they thought that the type of samples they needed for the particular inquiry they designed would be difficult or impossible for students to acquire on their own. For example an engineering design teacher brought in *dog-bones* which are pieces of bone-shaped metal designed for professionals to test material strength. During the workshop a high school life sciences teacher who teaches marine science brought in desiccated diatoms from an old fish tank:

> Since a fieldtrip wasn’t in the cards this year (although I think it will be next year), since there would be more creative and critical thinking involved and just, more authentic scientific observations plus the struggle and frustration in getting samples together and prepped if we include field experiences.

Teachers who used a guided inquiry approach designed several activities to support students through a series of steps to develop a hypothesis. In some cases, teachers wrote in their call-outs that they learned that they needed to include several more activities to develop their hypothesis because students had a difficult time understanding what it means to form a testable question or connecting the idea that once they developed their hypothesis, the research methods they designed should result in the gathering of
evidence that either supports or refutes a knowledge claim. As one high school teacher shared following a classroom observation “I needed to continuously ask the questions, is that method going to generate the data you need to answer your question and then how does that piece of evidence inform your question?”

A veteran middle-level teacher shared during an interview that she learned while teaching the unit just prior to the nanoscale unit that she needed to “scaffold in more steps to help students learn how to be able to examine a statement critically…they need to learn to experience disproving a hypothesis that they thought was reasonable.” She went on to say that during her nanoscale unit, she shifted her instruction plan further because, [students] "didn’t really make a hypothesis before beginning. Some who started by just observing the fibers with their eyes counted this as their hypothesis.” She said that she added three days to the unit to guide students through the process of developing testable questions after their initial SEM experience looking at various fibers, so that they could develop authentic questions based upon what they “noticed about the different fibers and thought about how knowing something about the variations might be helpful for solving their questions.”

One middle-level and two high school teachers designed their unit of instruction as an open-ended inquiry process. In this case, teachers provided the learning objectives and big ideas in nanoscale science to guide the inquiry; however students generated a hypothesis, designed the research methodology and chose materials to examine. Teachers
observed during classroom observations used formative assessment probes to guide group discussions but did not explicitly correct misunderstandings. Rather, each of these teachers reported that they asked questions such as, “why don’t you check out your sample under the microscope with your question in mind?” to guide students to test and debunk misconceptions on their own. When asked after class about this strategy, one of the teachers I observed replied that he thought “to take a positive approach to helping students to figure it out own their own; what they do they understand and what part of their understanding does not logically make sense.” Thus, teachers drew on their PCK to think of ways to use formative assessment probes to help students build on their own base of knowledge, guide their thinking and invite students to learn by drawing on specific problem-solving strategies.

In the case of the open-ended inquiry units, students conducted preliminary observations of samples prior to the arrival of the high-powered microscopes using hand lenses and optical dissecting microscopes with low levels of magnification to generate a series of preliminary observations for discussion. During an interview a teacher explained that these initial observations were intended to build background knowledge in preparation for the unit and to serve as a conceptual bridge between the preceding unit and the SEM unit. Teachers combined visual experiences with technical vocabulary used to describe the characteristics of specimens.
One of the high school teachers who used an open-inquiry approach wrote a call-out reflection that said that he asked students “to use specific scientific language to describe their thinking to ensure that they explicitly understood the technical vocabulary and conceptual links between topics covered in each unit.” Using this informal performance-based assessment, teachers said in their call-out reflections and in interviews they were able to detect evidence of how students’ understanding was developing and perceive gaps in students’ thinking or misconceptions. This information assisted teachers to prepare guiding or probing questions to support students to approach the topic from a new perspective rather than simply repeating activities that were unsuccessful in helping them to learn.

**Assessment of student learning.** Teachers drew on their PCK to incorporate a number of forms of assessment into their units. On the next page, Table 18 depicts the forms of formative and summative assessment teachers embedded in their units and the number of teachers who utilized each strategy listed,
Table 18

*Types of Assessments Teachers Listed in the Unit-Plans*

<table>
<thead>
<tr>
<th>Assessment Instrument</th>
<th>Number of Units that Included Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Student worksheets</td>
<td>14</td>
</tr>
<tr>
<td>Pre and Post Test</td>
<td>8</td>
</tr>
<tr>
<td>Class discussions</td>
<td>6</td>
</tr>
<tr>
<td>Peer Assessment Scoring Guide</td>
<td>5</td>
</tr>
<tr>
<td>Performance-based assessment on instruments</td>
<td>5</td>
</tr>
<tr>
<td>Task Book</td>
<td>4</td>
</tr>
<tr>
<td>Exit slips</td>
<td>4</td>
</tr>
<tr>
<td>Laboratory Journals with Scoring Guides</td>
<td>2</td>
</tr>
<tr>
<td>Class created database of pollinators</td>
<td>1</td>
</tr>
<tr>
<td>Student presentations</td>
<td>12</td>
</tr>
<tr>
<td>End of unit lab report</td>
<td>8</td>
</tr>
<tr>
<td>Posters gallery walk</td>
<td>7</td>
</tr>
<tr>
<td>End of unit quiz</td>
<td>3</td>
</tr>
<tr>
<td>Multimedia presentation with scoring guide</td>
<td>2</td>
</tr>
<tr>
<td>Consumer choice pamphlets</td>
<td>2</td>
</tr>
</tbody>
</table>

I begin with a discussion of the formative assessment strategies teachers involved in their unit of instruction. Interestingly, examination of the units of instruction, CoRe tables, call-outs and interview data revealed a dichotomy in how formative assessment is defined by teachers in the program. This dichotomy relates not only to how teachers think about what formative assessments are but also to how to use them to assess student thinking and how practice is informed students’ responses.

There appeared to be a learning progression among teachers beginning with those who utilized what Bennett (2011) refers to as using *evaluative listening* for correct use of terminology, to those who were observed using or referred to employing *interpretive*
listening to perceive the substance of students’ thinking to guide instructional decisions to *hermeneutic listening* skills wherein the instructor acts in both a learning and facilitative role. Some participants expressed in their CoRe tables and interviews that they thought of formative assessment in terms of instruments or quizzes that enable a teacher to gather evidence of student accomplishments so as to determine the future course of instruction. Another group of teachers thought of formative assessment as a process that enables perceptive teachers to gain insight into student thinking and learning. This difference of interpretation proved to be a topic of much debate among several groups during the unit-planning period. Bennett (2011) addressed this divide in much the way I came to think about the issue:

Arguably, each position is an oversimplification. It is an oversimplification to define formative assessment as an instrument because even the most carefully constructed, scientifically supported instrument is unlikely to be effective instructionally if the process surrounding its use is flawed. Similarly, it is an oversimplification to define formative assessment as a process since even the most carefully constructed process is unlikely to work if the ‘instrumentation,’ or methodology being used in that process is not well-suited for the intended purpose. ‘Process’ cannot somehow rescue unsuitable instrumentation, nor can instrumentation save an unsuitable process. A strong conceptualization needs to give careful attention to each component, as well as to how the two components work together to provide useful feedback.

(p. 7)

In all cases, teachers reported in their unit-plans and interviews that formative assessment scores were not included in the final grade and students were given multiple opportunities throughout the unit to correct their thinking. Fourteen of the units of instruction involved the use of student worksheets for students to fill out as they rotated through the stations. Although 10 teachers who completed their unit by the end of
February did not report assessing student work in the student packets until the end of the unit, four teachers reported during the interviews that they checked student work in the packets on a regular basis and then drew on these data to inform changes to the lessons that followed. Two teachers wrote in their unit-plan they developed together that they had their students use a technique known as an Interactive Notebooks using the Cornell Notes approach to record their laboratory notes. These teachers said during an interview that they checked the students' interactive notebooks daily and entered comments for students to respond to the next class period. Four teachers wrote in their unit-plans and shared during a final workshop presentation that they used an approach known as the Task Book System, a check-off system wherein students enter lab notes into a journal and then receive either formative feedback from the teacher or a stamp to signify that they have satisfactorily completed each of the stations tasks recorded in the task book.

Eight teachers wrote in their units of instruction that they used pre and posttests as both a formative and summative assessment. During the reflection period, five of these teachers reported in their call-outs that they drew upon the pre-test to inform minor changes to their unit. All eight of the teachers who use the pre and posttest approach said during interviews that because they were in the process of learning how to recognize, interpret and respond to student thinking about the nanoscale this year as they taught the unit(s) for the first time, the pre and posttest results informed their thinking about how to change the unit for next year much more than contributing to how they adjusted the unit or how they worked with students this year.
Five teachers used peer and group assessment scoring guides at regular intervals throughout the unit so that they could check on group dynamics and intervene as necessary. One teacher said that he did not institute the peer-review assessment until the end of the unit when it was too late for him to intervene and help adjust group dynamics. This teacher said during an interview that he plans to change his unit next year to include peer assessments at regular intervals rather than use the strategy as a summative peer-review. He said that he learned from this experience new ideas for how to anticipate student thinking and for how to respond to thinking in a reflexive manner. This teacher and others also emphasized that simply working with students on lab activities side-by-side expanded their knowledge of the content and how students approach learning how to use these two microscopes to explore content.

Five teachers wrote explicit criteria for performance-based assessments at the SEM and Leica in their unit-plans. For example, teachers created a scoring guide that also served as a check-list for students to use as they loaded samples and manipulated the SEM. This process generally followed a call-and-response pattern wherein the teachers asked the student to recite each step as she or he performed the tasks and then answer a set of questions related to what can and cannot be done with the instrument.

Six of the teachers explicitly listed class discussions as a formative assessment strategy. Examples of class discussion formats listed on the units of instruction plan were: think-pair-shares, popcorn style responses to teachers’ questions (either spoken or written on the board), parking lot responses (ideas that are out of context posted in writing to a centralized poster for later discussion), muddiest point discussions about topics that make
little to no sense to students, video clip response discussions and exit slip discussions. Four teachers explicitly described during interviews that the use of exit slips with follow-up discussions was an important strategy they used to ensure that students connected content addressed in activities to the learning objectives and to redirect students with misconceptions or missing knowledge.

Although other teachers in the cohort did not explicitly describe certain activities in the unit as formative assessments, teachers wrote scoring guides for final reports and rubrics for scoring student worksheets at particular points within the unit. When asked, teachers shared that they planned to share the scoring guides with students when they assigned activities so that students would be clear on proficiency-based expectations. For example, one engineering design high school level teacher said during the summer workshop that he anticipated that students could hold a common misconception that material stress is the same as stain. Therefore he wrote indicators into his scoring guide as a formative assessment to determine whether or not students completely confused these two concepts. This teacher expressed that doing so was important so that he could use a “just-in-time” teaching strategy and target “where they lost the thread so that I don’t turn them off by starting too far back when I ask them to think about certain ideas about the effects of different types of forces on materials.”

More experienced teachers and three novice teachers who recently took courses on educational assessment reflected in their call-outs and interviews that this first experience teaching the unit involved multiple approaches to interpreting assessment data. Teachers spoke about using evaluative listening skills as a first
step to identifying if students were able to correctly use appropriate vocabulary to describe concepts or processes. Although some teachers stopped there, most teachers described using interpretive listening skills in which teachers listened to the substance of students’ thinking and then made instructional decisions based on evidence of students’ depth of correct understanding and then building on logical elements to guide students throughout the inquiry process. The most adaptive of the teachers were not necessarily the most experienced teachers. In fact the one of the novice teachers and teachers nearly the culmination of their career were most able to use what Bennett (2011) referred to as hermeneutic listening skills in which the teacher was open to learning along with their students and about student thinking as it developed during classroom conversations and lab experiences.

Several mid-career teachers communicated during the interviews that the experience of being novice in the area of nanoscale science and technology was the most difficult aspect of the entire experience for them. Teachers shared that the feeling of not knowing the scientific and technical answers for every question placed them in a very uncomfortable state of disequilibrium, particularly in the area of knowing how to respond to assessment data. One teachers said that her lack of PCK related to teaching nanoscale science using an SEM, created anxiety because she was unable to infer from her students’ words the underlying causes of limitations to learning and engagement whether they were making errors, slips, holding misconceptions or truly lacked understanding. Because she knew that
each of these causes of limitations to learning require a different instructional action ranging from minimal feedback (for the slip) to reframing the entire topic (for lack of understanding) to the significant investment required to engineer a deeper cognitive shift (Bennett, 2011) she said that in many cases she was unsure as to how to precede.

Bennett (2011) claimed that the value of formative assessment is not realized until teachers are able to adjust their instruction based on the information they gain from the assessment. In most cases teachers shared that formative assessment feedback impacted the pacing of the class to assist students when they were confused and the student either needed help decoding readings or a topic needed to be reframed. However, several of the teachers proved to be inventive, either structuring the classes so that more advanced students helped those who are less advanced, or dividing the class so that the instructor could spend more time with students who are struggling, while more advanced students continued working through the station activities. During interviews teachers shared the idea that expanding the repertoire of opportunities for Project NANO teachers and participants in similar programs to explore various signals of student thinking could be embedded in teacher PD to draw teachers’ awareness words and actions they could be looking for as they test out instructional strategies with students throughout their nanoscale science units of instruction.

The nine teachers in the focus group spoke at length about their concern that students did not integrate content learned at the activity stations sufficiently to be able to recall that information one or two weeks later. Teachers’ observed that because students
forgot the smaller details, they were unable to connect those ideas to the bigger ideas described in the learning objectives. These teachers all agreed that dedicating more class time to processing new information and connections by doing activities such as instituting the use of exit slips with follow-up whole group discussions on a more regular basis might do much to remedy this problem.

Five units involved students in creating a product intended to educate the general public on a topic in science. One teacher explicitly listed in his unit-plans a formative assessment strategy related to his classes’ products. In this case, he had an advanced placement high school biology class of students create a pollinators database. This teacher wrote:

> Each group will image the pollen of the three flower species they have collected, and the pollen being carried by their pollinator; each group will then put the pieces of our puzzle together in an attempt to figure out what species are being pollinated by your *vector* and which vector is pollinating your flowers. Findings will be presented to the class.

As students put together the pieces of the puzzle this teacher said during the interview that he was listening to students argue and defend their case for which species is pollinated by which organism or vehicle (such as wind) that transmits the pollen. He said that based on his experiences listening to student argumentation this year, he is better prepared to adjust his questioning probes in response to students’ points made throughout their arguments next year.

Teachers emphasized the role of summative assessments in their classes as well. Indeed, all told, participants involved the use of seven different summative assessment strategies in their unit of instruction. For example, they said during the summer
workshops that a test or final presentation itself can help students integrate prior learning, help them retain what they have learned, and sometimes learn new material. Teachers also pointed out during the interviews and in their CoRe tables that students learn as they are reviewing material in preparation for a test. Teachers also claimed that summative assessments that are well aligned with course content and formative assessments can carry out their primary purpose of documenting what students know and can do, and thereby inform modifications of the course materials prior to being used again.

Interestingly, three teachers that chose not to include both a pre and a posttest included an end-of-unit quiz. These teachers wrote in their unit plans that the majority of the unit grade would be based on the end-of-unit lab reports and activity station worksheet scores. Eight teachers required that students submit laboratory reports; of these, three teachers required that students submit individual reports and five teachers required group reports with the names of the student or students who completed each section clearly labeled. Teachers using the group report format included the use of peer-review scoring guides as part of the final assessment.

Twelve units of instruction involved summative student presentations using PowerPoint or similar media to share their images and findings. Five middle school teachers and two high school teachers who all took the same section of the summer workshop together chose to involve their students in creating posters of their findings and knowledge claims and a gallery walk rather than group presentations. Four teachers chose to ask students to create a multi-media presentation to post to YouTube focused on educating consumers on scientific topics such as how different sunscreens work to block
harmful rays. And finally, one high school engineering design teacher involved students in creating annotated stress/strain curves for aluminum and brass from destructive testing experiments.

**Differentiation of Instruction**

Nearly every teacher failed to explicitly list plans to accommodate student diversity on the unit of instruction template. The following Table 19 depicts the forms of differentiation that were mentioned by teacher participants:

**Table 19**

**Forms of PCK related to Forms of Differentiation of Instruction**

<table>
<thead>
<tr>
<th>Elements of Unit</th>
<th>Categories of Thinking</th>
<th>Forms of PCK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Differentiations</td>
<td>Forms of Differentiation</td>
<td>Knowledge of assessment</td>
</tr>
<tr>
<td>strategies</td>
<td>o Activities with a variety of learning modalities</td>
<td>Knowledge of instructional strategies</td>
</tr>
<tr>
<td></td>
<td>o Activities that appeal to different learning styles</td>
<td>Knowledge of student thinking</td>
</tr>
<tr>
<td></td>
<td>o Responses to formative assessments</td>
<td>Knowledge of science content</td>
</tr>
</tbody>
</table>

Ironically, the teacher who did the best job explicitly describing various plans to diversify learning for special needs moved over the summer of 2012 to a school with a very low level of diversity and low number of high needs students. However, where teachers did provide data on their thinking about ways to differentiate instruction was in the student assessment section and in the learning community section of the unit-planning
template, in their CoRe and in their call-out reflections and in the interviews. In fact, during the focus group one teacher said that she did not differentiate for diverse learners and that she did not know how to do so; however when she heard other focus group members describe their differentiation ideas, she recanted that statement and said “oh wait, I did that too. I just didn’t know to call it differentiation of instruction.” Thus, as a researcher I am led to wonder how many teachers simply did not understand the meaning of the term differentiation and left the template page blank for this reason and not because they did not think about ways to adjust instruction to meet the needs of learners.

Teachers distinguished between pre-planning strategies to appeal to different types of learners and the type of responses they make in the moment while teaching. As mentioned elsewhere in this chapter, teachers wrote in their CoRe and in group discussions during the workshops and in interviews that they thought that the lessons themselves accommodated for various learning styles although only a few teachers described what they meant by the term “learning styles” by referring to kinesthetic, visual and audio learning styles. They pre-planned developmentally appropriate readings and videos, thought about how to structure activities with an appropriate level of guidance and challenge and pre-planned how to set of groups.

In fact, most of the units of instruction scored nearly all of the points possible in the learning community category of the unit-plan scoring guide. Interestingly, teachers in the focus group and individual interviews reported that consideration of the students working within learning communities or groups is where the bulk of the pre-planned differentiation of instruction occurred. They thought that by strategically placing
particular people together in a group, students would build upon one another’s strengths and compensate for their weakness. By created situated learning experiences involving multiple approaches to exploring scientific ideas, teachers said that they thought that students would compensate for and strengthen the learning experiences for all students.

For example, nearly every unit presented asked students to working together on activities that involved discussions wherein students shared observations and problem solved by drawing ideas that connect their new observations and content knowledge with prior knowledge. Each of the units developed required that the students build a body of evidence to communicate and defend their findings. However, although students were asked to describe the evidence they collected and to present their findings to their peers, with the exception of one high school level unit, students were not asked to rigorously defend their knowledge claims before their peers. In some cases, students’ were asked to make and defend knowledge claims in daily student worksheet entries and final written reports that each individual submitted to his or her teacher. In every case, the units involved opportunities for individual students to be assessment on their own performance rather than receiving a group score for the entire inquiry unit.

During the interviews and focus group, teachers also said that they differentiated instruction by involving a variety of learning modalities in the activity stations that met the needs of groups of students with a variety of learning styles. Teachers referred to instructional strategies such as modeling procedures coupled with verbal explanations and visual cues, scaffolding guided note sheets, practice writings, drawing and group discussions and performance-based assessments as ways they differentiated instruction
for various types of learners. Teachers with a high percentage of English Language Learners particularly emphasized aspects of the student worksheets that build vocabulary skills. They described a technique known as *discussion looping* in which terms and concepts are repeatedly reintroduced into conversation to develop familiarity with new ideas and vocabulary terms as the activities gradually increase in complexity. These teachers also emphasized performance-based assessments as an alternative technique for students to demonstrate what they know and are able to do. For example, one sixth-grade teacher with over 50% English Language Learners at an early stage of English language acquisition in her classes described the following activity that involved both verbal and non-verbal methods to prepare students to use the microscopes that allowed her to assess their understanding of the scientific procedures:

- I had them writing out cartoon pictures of how they were going to prepare their samples, so that they knew that when they went to make their samples, how they were going to do it. I had them do this activity here [pointing out a worksheet], like this one here, so they would say exactly step by step how they were going to do it and where they were going to put everything [on the stubs]. Then when they actually prepared their samples, I had groups talk each other through the steps while I watched them and made sure they followed their own directions with little questions here and there.

- All of the teachers emphasized the importance of considering group dynamics and how students influence each other to learn in their CoRes and in their reflections provided in the call-outs, interviews and focus group. A high school teacher related during an interview:

  - So one way that I tried to address differentiating the different levels in terms of the abilities of students in biology is that I picked their groups so that I could identify who I thought would be a team leader in each group and then have students who were really strong in science, students that maybe were a little timid...
or unsure of their skills so that enabled me, right from the start to have more control or just say, this is your team and all of the teams worked pretty well.

In some cases, teachers were observed to work with team leaders after class to check in on how students in each group were doing and discuss how to support students that were either disengaged or appeared to be struggling in some sense. When asked about this strategy during interviews, teachers reported that in many cases, teams were able to self-correct with very little guidance. However, teachers also noted that they did add lectures or work with individual groups that either they or the student team managers identified as needing extra assistance throughout the unit. The majority of this assistance took place at the beginning of each class during the time that the SEM was in the classroom and in the week following the departure of the instruments. Nearly half of the teachers in the sub-group with large class sizes lamented in their call-outs and in interviews that they feared that this assistance may have perhaps come too late for at least one group in each class that got off task and stayed off.

During this portion of the discussion at the focus group, two teachers reported that they made a series of informational/procedural videos to support students to prepare for and stay on track with activities even when the teacher was not available. In one case, the student teacher filmed the teacher while he modeled the procedures and discussed the related content the first time with the whole class. The teacher then made these videos available to students to refer to throughout the activities saying:

I thought, these kids will forget it immediately after they learn it and I don't have time to test them on the procedure and do that jigsaw that was originally planned. I did a couple of videos on the procedures… I videotaped it and I put it on the computer so the kids could watch it, and then I put in on YouTube, so it’s there
now. It’s not great, it’s solid, it’s not great, that’s something that this summer, there should be another video done, you know concisely at a middle school level and maybe at a high school level so that you can have a different articulation, cause you still need to keep it nice and clean for middle school so they, they get the safety parts but they don't lose all of the different parts.

**Summary**

In summary, teachers exhibited a wide range of metastrategic thinking and PCK used to negotiate the inclusion of nanoscale science and technology into the curriculum. Each of the groups and individual teachers involved in the 2012 Project NANO cohort approached this challenge as intelligent novices (Bransford, 2001) willing to enter into a state of disequilibrium to learn new content and skills and immediately apply this new knowledge to their teaching practice by building on their existing PCK.

As teachers approached various challenges along the way, they developed solutions to meet the everyday demands associated with working with large, diverse classes and technology that sometimes does not function in ways that one anticipates it will. In the following section, I report on changes to teachers’ metastrategic thinking and PCK that enabled teachers to rise to meet challenges this year and will inform their thinking in the future as they approach the increasingly common problems of practices associated with integrating novel science and novel technology into the secondary curriculum.

**Changes in Teacher Participants’ Metastrategic Thinking and PCK**

To examine changes in the teachers’ metastrategic thinking and PCK, I selected a sub-group of 14 teachers, 11 middle-level teachers and three high school teachers, who had implemented their units by the end of February of 2013. Because this group of
teachers completed the unit cycle by the end of the dissertation data-collection cycle, they were prepared to share their thinking to inform the sub-question, *how, if at all, do teachers’ metastrategic thinking and PCK change between the summer workshop and the reflection period following the implementation of the Project NANO unit?*

**Changes to Metastrategic Thinking.** Recall from an earlier section that teachers drew upon their metastrategic thinking to inform the development of their rationale during the unit planning phase for how to organize learning experiences for their students that would support the development and use of students' higher order thinking skills and learning content knowledge. The factors of metastrategic thinking teachers described during the planning phase were affordances and limitations of scientific tools, the influence of state content standards, science, technology and society and the type of unit, limiting conditions and factors that involve both affordances and limitations.

Here, I present changes to teachers’ metastrategic thinking between the summer workshop and the conclusion of the reflection period following the implementation of the unit. Recall that metastrategic thinking relates to a thinking that contributes to the development of rationales for how to design learning opportunities that facilitate students to learn content and to use and build higher order thinking skills. Teachers’ changes to their metastrategic thinking were: rethinking how to best sequence the unit within the science course, changing the unit by restructuring or reordering lessons to reinforce difficult to master fundamental scientific knowledge and skills, imagining ways to improve time efficiencies, establishing explicit group roles, rethinking elements of the unit they had deleted between the summer workshop planning period and completion of
the implementation of the unit, rethinking how much freedom to give to students depending on their readiness and limitations and adjusting the unit to accommodate for larger class sizes.

To begin, Table 20 provides direct quotations from teachers describing each of the units taught by members of the sub-group of study participants. Recall that in several cases, teachers co-developed units of instruction; thus, there are fewer than 14 different units provided in the descriptions that follow. With the goal of avoiding redundancies, I have selected only one representational quotation for each of the units taught by members of the sub-group of teachers.
Table 20

**Topics of the Sub-Group Units of Instruction**

<table>
<thead>
<tr>
<th>Grade</th>
<th>Science Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sixth grade, Integrated Science</td>
<td>“We did a unit on sunscreen and nano-particles, so I teach a health science research class.”</td>
</tr>
<tr>
<td>Sixth grade, Life Science</td>
<td>“What we wanted to learn was some comparative ecology so we looked at some of these critters, that was some of the things I was using students for: what are they interested in, what sorts of things they want to investigate and then what are they going to take away from the activity?”</td>
</tr>
<tr>
<td>Sixth grade, Integrated Science</td>
<td>“[I focused on] what they think their structure was and what they researched their structure to be and how that might be a mimicry that we can use for technology [biomimicry].”</td>
</tr>
<tr>
<td>Sixth grade, Integrated Science</td>
<td>“What I really wanted students to understand is that it doesn't matter how much you teach them about nanoscale or even micrometers, they don't understand how explosive this thing is so they see this little piece of paper and they can see how thick it is at 400x which is the minimum, they kinda get an idea like oh! Ok! [understanding scale with visual support]”</td>
</tr>
<tr>
<td>Sixth grade, Life Science</td>
<td>“We were finishing up our Ecology unit so, for the past 18 weeks we've been looking at ecology concepts with our sixth graders, started the year with outdoor school and then kind of continued to look at ecology concepts and this is kind of a, end of ecology unit.”</td>
</tr>
<tr>
<td>Seventh Grade, Integrated Science</td>
<td>“[We] developed a [seventh grade] unit on a crime scene investigation and it was a Red Fibers lab, [a] crime they were trying to solve and the nano served as one piece of data they needed to solve that crime and then they had to use all three pieces of data to determine who the criminal was.”</td>
</tr>
<tr>
<td>Seventh grade, Life Science</td>
<td>“I teach life science, we are just finishing up with the compound microscopes, the unit was called Inner Beauty.”</td>
</tr>
<tr>
<td>Eighth grade, Life Science</td>
<td>“For my students it was an introduction to some of our science inquiry concepts and then I also taught an abbreviated version with my science team, we decided to have me teach it to all of the eight graders in the building. I only teach half of them, so I taught it in a week and then we swapped kids and I taught it to the other kids the next week. So it got compacted a little bit to squeeze it into the two week time frame.”</td>
</tr>
<tr>
<td>High school Chemistry</td>
<td>“I teach [high school] chemistry and I taught a unit on matter, classifying matter, so basically things like purity.”</td>
</tr>
<tr>
<td>High school Engineering Design</td>
<td>“I have high school seniors and a few juniors in my classes. I added a unit into the Project Lead the Way curriculum right before the tensile strength unit because I know from past experience that many students have misconceptions about stress and strain. These are really important ideas to have clear so that they can be successful in the tensile strength unit, so I wanted to add this part to be sure they got it. Plus, this was the most logical place to fit in the SEM and the nanoscale.”</td>
</tr>
</tbody>
</table>
Rethinking sequencing the unit within the science course. Teachers did not explicitly share which of the changes to their thinking were the most or least important, so it would be presumptuous of me to say which of the ideas they shared are more important than others. Therefore this section and the following sections that describe the changes to thinking that teachers spoke or wrote about are presented in a non-hierarchical manner. I begin by describing what teachers shared about rethinking the sequencing of the nanoscale unit within their science course.

Participants in the focus group described how the initial experience of teaching their Project NANO unit informed new ideas about how to fit the unit in their science course next year. Teachers drew upon their metastrategic knowledge and built upon their PCK related to knowledge of the curriculum and knowledge of instructional strategies in two ways as they considered how to change the sequence of their units: when to fit this guided or open-ended inquiry process into the academic year and how to organize the order of the content in the unit, both individually described in this and the next section.

One representative comment offered by a novice high school teacher during the focus group discussion stated,

…another thing that might be different for me was that I did mine at the very beginning of the year, so we did one unit and then the very second unit was the SEM unit, so that also probably played a role. You know, we were still establishing classroom routines and all sorts of other stuff a month into school and then also throwing in this big independent project may have been too much for some kids.

A veteran middle-level teacher essentially echoed this idea when she said that although the Project NANO unit was not one of the first inquiry-based projects of the year, her unit
was designed as a much more open-ended process than the units she typically teaches in the fall. She said that although she valued the guided-inquiry nature of the unit she designed, unless she can recruit adult volunteers to help students while she is at the SEM, in the future she may need to put the unit closer to the middle of the academic year when her sixth grade students are better prepared for the highly independent nature of this unit.

**Thinking about how to improve the structure of the unit to facilitate the development of higher order thinking skills.** During interviews and in their call-out reflections teachers discussed changes in their metastrategic thinking related to how to scaffold the development of scientific skills and knowledge to move students into applying higher order thinking skills. For example, a novice high school chemistry teacher who taught the Project NANO unit as the second unit of the academic year in September thought he could use the SEM images themselves to introduce the concepts of homogenous substances and heterogeneous mixtures, suspensions and colloids saying:

> So if you look at samples and see as you zoom in more, if you use the light microscopes verses the SEM, you can see how it changes if you look at how one crystalline structure is different than another crystalline structure and all of the sudden you realize that there are different salts there, not just one…So, purity and also classifying stuff based on heterogeneous vs. homogeneous mixtures, pure substances, that sort of thing and using the Nano tool to get a little bit closer [look] to use for classification.

This teacher and another chemistry teacher who also taught a percent composition unit learned that it was difficult for many of students to understand “brand new concepts while going through the stations.” This teacher reflected that:

> If I had pre-taught them about classifications of matter and then when they went to the lab stations they already understood that’s heterogeneous, that’s homogeneous and then they can apply it once they have the fundamental
understanding, then it’s much easier for them to make the connections…so I'm just saying that they can make those bigger connections because they already have those smaller connections. My students in particular were just working on making those smaller connections, so it’s really hard for them to interknit those big ideas when they are just now learning the smaller aspects of the overall concept.

When this teacher was asked what he meant by the notion of “interknitting big ideas,” he referenced making connections between ideas so that students are able to draw upon this knowledge to analyze, evaluate and, in the case of this unit, categorize materials. Another teacher in the focus group interjected that he too was interested in students interknitting concepts but his sense was slightly different, given his interest in supporting students’ abilities to draw on interdisciplinary concepts to understand natural processes. For this second teacher higher order thinking skills means the ability to apply critical thinking skills to understand how concepts related to friction that are described one way in chemistry relate to the same concepts that are discussed in physics using different terminology and lab experiments.

All of the teachers interviewed spoke about ideas they were considering for how to help students make connections to the learning objectives and big ideas involved in the unit. One teacher shared changes to her thinking:

I think for biology, more front-loading in terms of nanotechnology related to the content, more scaffolding would have been good. I did have one reading which they really loved called Prom 2045 and that was a great hook to engage them at the beginning of the unit, so maybe something at the end that’s some kind of closing article or closing piece that gets them back into the literature and really sums up the unit.

Teachers also spoke about structuring their unit to have more frequent discussions and other activities to assist students to maintain a growing sense of how the content
addressed in the activities connect to the learning objectives. As mentioned in an earlier section, teachers used exit slips, group discussions and online discussion boards. When some teachers shared these ideas during the focus group, other participants asked for elaboration and took notes saying that these ideas provided solutions for challenges they had not resolved in their own minds. It was interesting to note that the teachers who asked for additional information represented the full range of career stages; they were novice, mid-career and veteran teachers.

**Rethinking how much freedom to provide students.** Seven of the 14 teachers explicitly wrote call-out reflections and spoke during interviews about adjusting the amount of freedom they allowed students to select their own samples and design their own scientific inquiry. For example, one of the chemistry teachers who taught the percent composition unit said:

> I felt like I wanted to give my students the freedom and flexibility to encourage that academic autonomy to collect their own samples to examine and categorize as homogeneous or heterogeneous as a first step towards figuring out the percent of the composition. This may have contributed to some students failing to connect the smaller concepts to the big ideas. I think that more guidance in terms of that integration by comparing four different materials as a whole group by looking at optical and SEM images projected onto a large screen using the overhead projector, would have been helpful; one idea would be to have everyone focus on the same theme [at the same time] and to dig deeper together to really have that integration more seamlessly there.

Both of the chemistry teachers who taught the percentage of a composition unit indicated that the four materials they would examine and describe as a whole class would be a pure sample, a mixture, a colloid and a solution. Doing so would help ensure that students knew what characteristics they should look for to analyze in their own sample,
rather than trying to figure it out for the first time on their own by looking at the samples with the microscope and attempting to interpret images without this reference point and enough time to figure it out through iterative background searches and microscope sessions. Interestingly, this observation echoed that of another teacher in the program who described his own learning process during the focus group, indicating “I found it hard to struggle with learning about something, reflecting about it and starting to build a unit all at the same time, just mentally.”

Other teachers described changes to their thinking as a result of finding that some of the samples students brought in either did not work with the SEM or that there were too many of the same sample to have enough variety in the class to make the experience of examining specimens engaging for students. Interestingly, several teachers said that during the science inquiry process at the summer workshop they realized that their initial ideas for their units were not going to work either because the samples they chose were wet, oily, magnetic, or quite difficult to mount on a sample stub to put in the SEM or because their samples charged so quickly it was difficult to capture quality images. They said that they decided to switch to another idea by Wednesday of the summer course. However, despite this drawback, these teachers expressed that they learned valuable information from this experience that attuned them to test whether or not it would work to allow students to bring in their own samples. As one middle-level teacher explained:

I remember not just for us but for a lot of people in our class, we had the similar issue as the kids. We had these great ideas and then you get it under the SEM and you’re like, oh! that is way too big or it’s not going to work. And so then there wasn’t a whole lot of time to do some background research or maybe even find different samples, since everything was so condensed, once you got to that point,
it was like now what am I going to do! It’s like I need to totally rethink my whole concept and I'm still trying to get pictures taken. And so if there was some time built in where you could just do a little bit more playing around; here are some of the things that we know work, here are some things that don't work, let’s all take pictures and then get to the point where you are working on the actual lesson and kind of taking your own pictures...

Some of the changes to teachers’ thinking about this question of how to provide students with both freedom and support occurred during the focus group conversation itself. For example, during the focus group one teacher novice teacher shared:

I found that [the students] all brought the same samples, every single kid had a piece of an eraser, pieces of paper from home, a piece of hair, you know, the same four samples kept coming up over and over and over so it was really interesting and so I don't know if I'd make a list next time or something or prompt them on what to bring or something a little more so that we can have more varied set of samples.

In response to this comment a mid-career teacher offered ideas that the novice teacher said he would consider. He said that he allowed students to bring in samples plus he brought in backup samples just in case the materials students selected did not image well or could not be safely placed in either microscope, noting that:

Kids that didn't have really good samples, you didn't want to say those samples wouldn't be great [laughing] but then you could say, well why don't you throw some diatoms in there as well and so they scanned in well, kids were excited about them and that was helpful setting something up that’s really easy to have.

In addition to the conversation about how to select samples, several teachers shared in their call-outs and during the interviews that they developed new ideas related to how to re-structure sample preparation lessons. For example, one teacher said during an interview:

Ok, so this kind of ties with better ways that I would teach the content through looking at different strategies. So the first one really would be whole class stub
preparation, I tried to have that as a station and I just felt like I was having to run back and forth too much to re-teach; I don’t mind the re-teaching part of course, but for ease of understanding I want everybody to do the sample prep together and be really clear and really direct...so I feel that whole class broad instruction would have been good for certain things, like sample prep and maybe modeling more explicitly what to do at each station.

**Thinking about how to improve the efficient use of time.** Every teacher involved in the study thought deeply about time constraints since they knew that they would have the opportunity to check out the SEM and Leica for only two weeks before the university shipping department moved it to the next classroom or school. In the units of instruction, CoRes, during classroom observations and in interviews teachers wrote and spoke about strategies they used to prepare the students to, “hit the ground running when the SEM arrived.” For example a sixth grade teacher shared during an interview:

> I tried to do some pre-teaching for each of the stations on what to do and what to expect, I gave them a handout that had the written instructions, I demonstrated each station, and then I did that each day as a reminder for the next group of kids. So modeling, that was it.

However, during this conversation related to what teachers referred to as “front-loading the unit,” the topic of sample preparation came up as something to change next year. All of the interviewed teachers referred to sample preparation time as, “wasted SEM time” with some teachers saying their students, “lost two or three days preparing samples while the SEM was in the room.” This group of teachers referred to the idea in science that correct sample preparation is an essential skill and is, therefore, worthy of taking class time to carefully teach before the SEM comes to the classroom so that students do not rush through important procedures and make mistakes in their rush to use the SEM. As
one teacher put it “garbage in, garbage out, so yeah, the sample prep skills are essential to the whole inquiry.” Several teachers wrote in their call-outs and shared during interviews and the focus group that next year they plan to request that the stubs arrive at their schools a couple of weeks before the SEM and Leica so that they can have students prepare samples and prepare stubs and slides prior to the arrival of the SEM. One teacher related during the focus group discussion:

> It was really hard just getting the SEM and not getting [stubs] it would have been nice to get [stubs] ahead of time so we can prep those ahead of time so that we don't get stressed about that as an issue, because everything came all at once as opposed to steps, that could be helpful.

Despite well laid plans to use the time wisely while the SEM and Leica were in their classrooms, teachers shared in their call-outs and during interviews that in practice they experienced difficulty balancing the time students spent at each station because students wanted to have more time on the SEM. One high school teacher related during the focus group discussion:

> Each team wanted 30 minutes to an hour on the SEM and in the future I want to be a little stricter about stub preparation and number of stubs that students prepare…some kids prepared three or four stubs with four samples on each stub, which is way too many samples to look at in the time allotted. I need to be bit more strict on the time limits for the SEM and to institute a sign-up sheet for each station, so we all know what the rotation is and we don’t lose time trying to remember where everyone has been and still needs to go. That way I’m not as stressed trying to track the rotations and kids can anticipate their next station, which is especially good if they finish the task early on a station and have time to prep for the next one.

**Considering explicit group roles.** Unlike the more experienced teachers who established team managers for each lab group, the less experienced teachers did not follow this same pattern. The following quotation is typical of comments made by the
middle and high school level novice teachers during classroom observations and in interviews:

...group roles at stations, I did that at the SEM station, but not any of the other stations and that again makes students feel that the instruction is more individualized and helps students to feel a greater level of accountability for what they are learning about, so they know what they are doing and importantly why they are doing each activity and how it relates to the big ideas.

These teachers also shared that their group sizes were too big, which left too many students with nothing to do. They stated that one of their goals for the summer 2013 follow-up workshop is to figure out specific roles for members in groups of no more than three or four students.

**Rethinking elements deleted from their unit.** All of the teachers in the subgroup reported in the interviews that they spent eight to 20 hours revising their units after the summer workshop before implementing their plans. One of the changes teachers reported making regards the attempt to reduce the length of the unit by removing elements from it. For example, several teachers said that they removed readings and discussion time dedicated to bio-ethics. However, during the interviews three teachers shared that they were forced to rethink this decision because students essentially forced the issue by asking questions related to unintended effects of releasing modified molecules into the environment.

Another element that teachers said they removed or reduced in the units they designed during the summer workshop related to applications of nanotechnology in industry. Teachers indicated during interviews and in call-outs that they left in place one station that included a short video on applications of nanoscale science, but cut out some
of the readings and group discussion time. It turned out that parents and students sent teachers web-links with videos and news stories they wanted to be shared with the entire class that address medical science applications of nanoscale medicines to site specific regions of the body, water purification systems, solar energy applications and other applications that excited students. Parents and students also brought in books, professional journals, popular science and technology magazines and even tags off of rain coats and other products that use nanoscale technology in some way. In response to family and student encouragement, teachers incorporated these materials into the unit after the SEM and Leica were gone, offered extension options and promoted the idea that students consider drawing on ideas found in these materials for science fair projects or consider pursuing their interest through internships in local industry. Indeed, according to follow-up emails from teachers to the researcher, two middle-school students are now interning with Intel Corporation to use an electron microscope to research alternative fuels and several middle-level and high school students who drew on nanoscale science or technology for their science fair project won awards in their competition categories for their projects.

**Taking in account accommodations for larger class sizes.** Due to substantial budget cuts to area public schools this year, all but two of the teachers experienced significant increases in class sizes. Several of the teachers added to their call-out reflections following the focus group that they had gained new ideas from their colleagues about how to accommodate for larger classes. For example, during the interviews and in call-outs two novice teachers cited the mid-career teachers who had
shared on their CoRes and unit plans that were posted on the Project NANO website that they accommodated for large class sizes by setting up paired stations (or two of each station) and by “flipping the curriculum” to have students do background reading and watch videos as homework so as to allow for more lab time in class. Teachers also described new ideas for how to organize sample preparation ahead of the arrival of the Project NANO toolkit so as to enable the first groups of students to be prepared to begin the SEM rotation on the day of its arrival, thus gaining up to two days of tool-time that was lost to sample preparation this year.

Teachers also described ways to shift students from the role of passive receivers of peer-presentations to active participants using scientific argumentation. Teachers voiced during interviews and following classroom observations that they had observed that many of their students were less inclined to participate in two-way conversations in large groups, and that this is especially true of students with special needs. As a result, rather than serving as an interactive summative experience for a unit, student presentations tended to involve one group of students after another reciting virtually the same data and observations and for the most part, stating knowledge claims with little to no classroom discourse to follow.

Several teachers in the focus group said that they learned from their colleagues in the program that switching to having students participate in poster presentations with gallery walks increases students’ use of high order thinking skills and that for this reason, they plan to switch the final lesson of their unit next year to poster sessions. Teachers described their idea that poster sessions require that students examine each other’s data
and knowledge claims, and that they ask questions of the presenters. During the interviews teachers made the claim that they planned to adopt this strategy next year because this one-on-one experience involving scientific reasoning and argumentation requires not only that students report their data and findings, but also that they draw on evidence to develop argumentation skills. Thus, learners engage with the topic and each other in such a way that requires that students draw on the language they just learned to describe the knowledge they are in the process of acquiring and using higher order reasoning skills.

Teachers also described in their call-outs and in interviews ways to draw on the help of adult volunteers to accommodate large class sizes. Teachers noted that because they cannot be everywhere in the classroom at once, they could maintain the rigor of the activities in the unit with the assistance of well-prepared adult volunteers, as described earlier in this chapter. Focus group participants took this idea several steps further, brainstorming ways to structure the preparation of volunteers to work with students to as one teacher put it, “actually do science, not just baby-sit kids.”

For instance, in anticipation that students might not be proficient at using identification keys, a high school biology and chemistry teacher shared her new idea to involve an adult expert with the necessary expertise to assist students in learning how to identify diatoms: “I made a contact with a diatom researcher for identification help; it would be so neat for students to have a connection with the scientific community in an authentic way.” Informally, she spoke about how integrating technical references and expert support into the unit would potentially increase students’ awareness of how
scientists negotiate the task of identifying particular features of specimens useful for categorizing species by drawing on tools available in both analogue and digital forms.

Teachers also developed a set of recommendations for preparing adult volunteers such as scientists and engineers to work with students to conduct authentic inquiry. During interviews they recommended that Project NANO provide either a summer or fall volunteer training in a centralized location focused on preparing volunteers to support students using the SEM and Leica so that the teacher is free to circulate around the stations to support lab groups. Several teachers volunteered that they would be willing to participate as co-trainers for a two-hour training during which time volunteers would choose which grade level they want to support and/or the discipline of science or in engineering they wish to serve. The volunteers would then receive information on the learning theories and instructional strategies teachers have developed to give volunteers a sense of what to expect in advance of their classroom visit.

While some teachers in the interview discussions balked at the idea that volunteers need to know the learning theories implicit in the unit, others argued that because they are not suggesting scripting student facilitation on the microscopes. They emphasized their ideas that it is important that volunteers understand what it means to facilitate students using a social constructivist approach so that the experience does not become a lecture but rather a true guided inquiry learning opportunity for students. Teacher participants in the focus group agreed to set aside time during the follow-up workshop to further discuss the idea of how to prepare adult volunteers who can work
with either specific classes or perhaps more than one school (which they subsequently did do in June of 2013).

In this section, I addressed changes in teachers’ metastrategic thinking as a result of their reflective experiences teaching their nanoscale science unit of instruction for the first time. In the next section, the subject will turn away from changes in teachers’ metastrategic thinking related to how they will structure the unit differently next time to teachers’ PCK related to how they will teach elements of the unit in a different way based on what they learned this year.

**Changes to Pedagogical Content Knowledge (PCK)**

Teachers reported a number of changes to their PCK as a result of their experience in Project NANO. The most obvious changes to PCK for the entire sub-group of 14 teachers are gains in scientific content knowledge including knowledge related to analytical affordances and procedural skills related to the use of the SEM and Leica. According to responses teachers provided on the background section of the pre-survey, none of the teachers had prior experience working with a Phenom model of an SEM or experience teaching science with the instrument. All 23 of the teachers gained experience using both the SEM and the Leica and learned how to instruct students to select, prepare and load samples during the summer workshop. Furthermore, all of the teachers in the sub-group shared that during the implementation of their unit they learned new ideas for how to guide students through operating the functions of each microscope, optimizing and transferring images. They also reported in their call-outs and in interviews gains in
knowledge related to conceptualizing and describing the nanoscale and related concepts. Classroom observations further supported this claim.

Teachers in the sub-group reflected on both their gains in terms of technical solutions to a myriad of challenges and new PCK that informs emerging ideas of what they will do in the future to change their units of instruction. As is the case with teachers’ metastrategic thinking, teachers did not explicitly express changes to their PCK in a particular order. Teachers did emphasize solutions to technical challenges, however they did not stress that these solutions were more or less important that the pedagogical changes in their thinking. Therefore, rather than ordering changes to teachers’ PCK in order of importance, the following section is logically organized by first listing pedagogical changes, then a technical solution followed by gains in scientific content knowledge.

I report out gains in science content knowledge in a separate section to highlight evidence that informs the sub-question, do teachers demonstrate scientific content knowledge gains in response to the 2012 Project NANO summer workshop? This section remains focused on data that informs the research question, how do teacher participants in the 2012 Project Nanoscience and Nanotechnology Outreach (NANO) program negotiate the inclusion of novel science and novel technology into the science curriculum and the PCK portion of the sub-question how, if at all, do teachers’ metastrategic thinking and PCK change between the summer workshop and the reflection period following the implementation of the Project NANO unit?
Changes to the sub-group of teachers PCK are: consideration of instructional methods to assist students with connecting content with learning objectives, new ideas related to how to facilitate sample selection and preparation procedures, consideration of instructional methods to assist students with the development of argumentation skills, new ideas for differentiation strategies to meet the needs of diverse learners, consideration of instructional methods to counteract the negative effects of time constraints on student thinking, and consideration of instructional methods to counteract the negative effects of time constraints on student thinking, creation of an annotated databank of photo micrographs and gains in science content knowledge. I begin with a description of changes to teachers' PCK related to assisting students with connecting content addressed in the station activities, class discussions and lectures with the unifying concepts and learning objectives.

**Instructional strategies to assist students with connecting content with learning objectives.** Every teacher in the sub-group ($N = 14$) indicated either in their call-outs or during the interviews and focus group discussion that they felt concerned that students were having difficulty connecting the concepts addressed in the activities to the learning objectives and big ideas in the unit. Thus, in addition to the structural changes mentioned above, teachers built upon their PCK related to potential changes to instructional strategies.

For example, teachers who used the exit slip strategy discussed in call-outs and interviews how in the future they might use this strategy on a more regular basis throughout the unit to check student thinking in time to adjust lessons to accommodate
for any misconceptions or lack of knowledge and to build upon knowledge they demonstrated in writing on the exit slips. One teacher who used the interactive science notebook approach suggested to his fellow focus group members that they might want to consider writing up daily questions that students respond to in their journals immediately as they enter the class each day. He said that this instructional strategy can assist learners to remember what they did the day before and how these activities connect to the learning objectives and big ideas. In response, focus group participants said that students could then draw on their ideas from these “free writes” to engage in whole class or lab group discussions about how content and skills they learned yesterday connect to today’s learning goals and how the content on any given day connects to the big ideas articulated in the learning objectives written on the board each day.

Teacher participants stressed during the interview they learned that waiting until the end of the each week or the end of the unit to do activities that help students to make connections between the content addressed at each activity station with the learning objectives and big ideas is too late for most young people. They expressed that based on this observation they now think that frequent check-ins are necessary to ensure students develop strong conceptual links that they are more likely to remember.

Teachers listed, in their call-outs and interviews, both technical questioning probes and topic-specific content probes they could use to build upon students’ knowledge shared during either class or lab group discussions. For example, one teacher wrote a call-out that he noticed that students seemed to have trouble understanding the concept of luminosity and distinguishing a luminous surface versus an electron charge on
the surface of a sample in the SEM. When asked about this idea during the interview, the teacher said that he will integrate a new station into the unit next year where students will look online at materials with various characteristics including luster and have them write about what they see before they spend time looking at samples with the SEM and describing the luminosity of their sample. He shared that he then plans to project images on the overhead with various levels of luminosity to next class, and ask students to first write and then publically defend their argument as to the levels of luminosity versus electron charging of the materials in the images.

**New ideas about sample selection and preparation procedures.** Teachers built their PCK related to facilitating learning sample preparation and mounting samples on stubs for the SEM. Properly selecting and mounting a sample on to a stub is one of the most critical steps in working with the SEM because an improperly mounted sample may either fly up into the machine and stick to the detector and break the instrument or limit its capability. This mistake may cost thousands of dollars to repair. Additionally, if a sample is not correctly oriented on the stub, it becomes difficult or impossible to view particular features of interest. Furthermore, if fingerprints or debris are pressed into the carbon mounting tape along with the sample, the sample will be contaminated.

Teachers drew upon the form of PCK related to knowledge of science content (scientific procedures) and knowledge of students to determine different techniques for working with students to mount samples. Two groups of middle-level teachers wrote in their CoRes that they were unsure that younger students would have fine enough motor skills to use double-sided carbon tape, so they decided to either mount samples for
students or provide extra carbon tape to accommodate for mistakes. In the interviews, these middle-level teachers expressed that students surprised them with their dexterity and their creative solutions for how to best secure and safely position samples on the stub to maximize the view of desirable features. For example, students experimented with carbon tape to mount certain types of samples, debated the benefits and limitations of carbon tape for mounting particular samples and then experimented with using carbon glue and a combination of both carbon glue and tape.

In their CoRes, high school teachers expressed confidence that students could successfully mount samples, but then refined these ideas for how to facilitate sample preparation and mounting in their call-out reflections. For example, a high school biology teacher wrote a call-out reflection that said, “carbon tape worked well with pressing samples into the surface of a clean table. Should cut hair samples to have an ‘edge’ to see internal structure and have a cross-section.” Other teachers had their students experiment with using carbon glue to mount insect parts only to find out that splatters of glue distorted the morphological features of specimens. Thus, teachers wrote in their call-outs that students noted that specific materials such as butterfly wings, diatoms, feathers and insect legs are best mounted with carbon tape so as not to obscure the sample.

Teachers also reported in their call-outs and in interviews about student experimentation with using a combination of carbon tape and a small dab of glue to firmly secure specimens to stub, which in some cases required repeated attempts to avoid glue splatters and seeping of the glue over the top of the specimen. Students logged their sample preparation and mounting experiments in journals. Teachers reported that they
carefully reviewed student’s scientific journals to inform their own thinking about how to best facilitate this process next year. For example, several teachers said that they plan to compile entries in the students’ science journal to share with students next year and ask them to add successful techniques to a group log as they experiment with preparing and mounting new samples. This collection of techniques documented in the group log will then be used to annotate the databank of Project NANO images.

**New pedagogical ideas for how to teach the use of each microscope and about the difference between the optical and electron microscopes.** Several teachers reported that they felt a great deal of anxiety about teaching students how to use the SEM and Leica and turned to classroom observations in more veteran teachers’ classrooms to gain deeper understanding of how each instrument works, what type of analysis they allow one to do and how to facilitate students in using the instruments. They shared that they learned from observing their peers and coach to scale up questions from very rudimentary queries related to using the instrument and remembering to clearly label samples so that students know what they are looking at under the microscopes to topic specific inquiries that asked student’s to engage the use of higher order thinking skills to analyze, evaluate and categorize or create knowledge claims based on evidence. Teachers also spent time with their coach reviewing how to use the instrument and talking about how to facilitate students using the SEM and Leica.

For example, teachers communicated during classroom observations and conversations following those observations and during interviews that they learned new techniques for using the Topo A and Topo B views on the SEM to check to see if a
shadow is being cast from a ridge-like feature or if the darkness on an image is actually pigmentation. They also reported that they learned techniques such as “bouncing” from one area on a sample to another to avoid charging in an area of interest. In relation to pedagogy, they indicated learning questioning probes that focus students’ attention on particular characteristics in a sample without completely telling a student for what they should be looking. As one teacher related during an interview:

I did have my coach come in the day the kit [the Project NANO toolkit with the SEM and Leica] was delivered and he did just walk me through [the controls] again, and he came in the next day, so that was the first day with kids and I was like looking over, what’s he doing, what’s he saying, how’s he doing that to see how he is able to get kids to be able to move through…The thing about my coach is that he is really engaging with the kids, so it’s not that he is just sitting there running it but the kids were like getting things out of it and I’m like trying to pay attention to how he’s doing it, cause I’m like ‘wow!’ you know the way he’s walking them through it, he is doing it quickly, there is a time factor, but also they’re getting it, they’re really getting it. [My coach used prompts such as] ‘what is the feature there? Can you get closer to see what it is?’ and ‘did you capture images of different parts of the sample and different samples at the same scale for comparison?’

Teachers in the focus group also spoke about drawing upon ideas from colleagues to prepare students’ knowledge and skills related to microscopes in a more general sense.

One teacher emphasized during the focus group discussion:

I also spent the week before, since I knew that I’d have them [the SEM and Leica] for a limited amount of time, building as much background knowledge as I could. So we practiced using the compound light microscopes before we watched a YouTube video to show about the scanning electron microscope that we were going to have so that kids could see it before it was actually in the classroom, because once it was there, it was like, hit the ground running and we’re using it.

Teachers found readings and videos that they felt did a better job at describing the technical differences between how the SEM and Leica work then the materials that were
provided through the workshop and Project NANO website did. They shared in their call-out reflections that once they felt more confident about their own grasp of the concept of electron backscattering (which is how the SEM works) they were better able to select developmentally appropriate videos and readings for their students. That said, several teachers in proficiency-based schools said during interviews and the focus group discussion that they provided a selection of readings with a variety of difficulty levels for student to choose from to read. They provided this choice to ensure that each individual was provided with options that suitably challenged them to stretch their skills. However, as is indicated in the following quotation from a sixth grade teacher, several educators were worried that students were not necessarily self-aware enough to choose a suitably challenging reading option or chose to summarize the most complex ideas found in the articles they chose:

I looked and found articles that were hopefully easier for them to understand. They had to read through the article and put it in their own words somehow or draw a picture. So drawing the picture thing was good for a lot of the kids who, there is no way they would have even gotten through the easy article otherwise. So that worked well, but then I found that they [students] would just go to the easy thing [concepts in the article] instead of trying to think, ok, how does this work and how do I explain it?

Teachers in the focus group asked their colleagues in the interview to write posts on the Project NANO Google group website to share descriptions of how they facilitated students to prepare samples and use the SEM. For example, teachers were particularly interested in viewing the narrated video a teacher made to step students through the procedures. They also requested that colleagues share specific lessons plans with web links to the readings and videos they used. Teachers said that they had learned from what
they heard during the interview and that they asked for colleagues’ resources so that they could potentially integrate these lessons and resources into their own units and share these ideas with other Project NANO teachers in their school or feeder school. Thus, the intention of further facilitating the development of an active community of practice to support teachers’ learning progressions appeared to be an important factor in contributing to changes to teachers’ metastrategic thinking and PCK.

**Assisting students with development of argumentation skills.** All but one of the teachers in the sub-group required that student groups do final presentations in the form of either a poster presentation or PowerPoint or Prezi group presentation. Following the students' final presentation which I observed, one high school biology and chemistry teacher said of her students: “They did an excellent job at finding the connections and then presenting them as well, with their images…and then making comparisons.”

However, the majority of the teachers realized during the reflection period that although they did require students to publically present their images and explain what they found, they did not require that students defend their arguments with their peers beyond the members of their own lab group. Teachers disclosed in the interviews and the focus group discussion that they asked students to make and defend claims in the final written report or in the worksheets or both rather than in the presentations. They said that they found that students either failed to make and defend evidence-based claims in their report or attempts to do so were problematic. Teachers said that perhaps having practice defending evidence-based claims prior to the finalization of the report might assist students to develop scientific argumentation skills.
During the interview, several teachers shared how they organized their unit this year to scaffold experiences to develop scientific argumentation skills. One teacher declared:

They presented what they found, what they think their structure was and what they researched their structure to be and how that might be a [bio]mimicry that we can use for technology. And then we are making posters for our project and in a month we'll probably have posters up, and then they are writing a reflective paper on nanotechnology.

To provide an example of the type of data students presented, in Figure 13, here are two comparative images captured by a middle-level student in one of the classes that engaged in a unit developed by one of the teachers in this group that explored the concept of biomimicry. Students in this class presented evidence such as comparative images as evidence used to defended knowledge claims using the poster presentation format.

Figure 13. Biomimicry comparison of gecko feet with gecko tape surface. Source: Group of middle-level students.

The teachers who collaborated to develop this unit explained during an interview that rather than waiting until the end to have groups make one final presentation, they included frequent group check-ins for students to present their evidence such as
comparative images with measurements and discuss what claims could be made about their evidence. Then, based on feedback from the whole class, lab groups discussed their evidence and reconsidered their claims, all in preparation to create a final poster for a gallery walk—a method in which student work is presented on professional conference style posters and the rest of the class reviews it as if viewing it in an conference poster session where students make and defend claims with each person who visits his or her poster. These teachers emphasized that because the gallery walk experience was not to be the first time students had seen and heard the evidence and claims, students would be better prepared to engage in conversation, ask for elaboration of thinking and in some cases, even challenge claims and question evidence.

Teachers in the focus group responded that they liked the progression of skill and knowledge building inherent in this approach and that this summer they would redesign their units to include similar opportunities for lab groups to operate in ways that they think professional lab teams function to support, challenge and add to the scientific thinking or engineering design iterative process of discovery.

**New ideas for differentiation strategies to meet the needs of diverse learners.**

Despite the fact that teachers in two school districts emphasized during the summer workshop and classroom observations that their classes of students were grouped by what the districts refer to as *ability levels*, each teacher developed only one unit of instruction to teach rather than designing separate units specifically for the different
ability level classes. Rather than developing separate units of instruction, teachers described differentiation strategies using activities that employ different learning modalities to appeal to multiple learning styles, as well as utilizing formative assessments to inform teaching moves. However, teachers in the two school districts that group students by ability levels reported during interviews and in call-outs that this level of differentiation in their unit was not sufficient to accommodate for differences among the distinctly different groups of students in each class.

Recall that three of the school districts involved in the study give students a mathematics placement test at the beginning of the year that determines the cohort of students in which they will be placed—either a so-called “low-ability group” or a “high-ability group” to use the districts’ terminology. Both middle-level and high school teachers in the districts that track students in this way reported a high level of student success in the so-called high-ability level class in which they taught their unit in; yet, in many ways the unit was less successful for the so-called low-ability groups. Teachers reported that their classes with a high percentage of students with special needs had trouble working independently, decoding instructions at stations, connecting the content in the activities to the big ideas and learning objectives, solving mathematical problems independently and generally staying on task.

1 Please note that the teachers used the language of “ability grouping” and that this term was not selected by the researcher to describe students.
Rather than expressing a need to alter the unit-plan itself for special needs students by creating two or more separate plans, teachers expressed that they wanted to maintain the rigor and general high-level of expectations of learning for all students, but change the way they work with individuals to support student success. When asked about these call-out reflections during an interview, one teacher shared:

I felt that the structure was too rigid to do that [differentiate instruction] on the fly, whereas definitely this year my teaching has changed by each [class of students], I mean, absolutely…survival, but I can do that because you know I’m not pigeon holed into one thing [standing with the SEM throughout the class period], you know I’m not, it’s just the structure, it’s just as I talked about with you before, it’s just physically having to be next to the machine [SEM] was my biggest problem.

So once again, a solution strongly reiterated by teachers is their need for scientifically trained adult volunteers in the classroom that would allow the teacher to circulate around the activity stations and assist students to perform the task and understand the content. To be clear here, teachers did not say that they intended to reduce the rigor of the overall experience for students. Instead, they emphasized that although materials may be chosen to accommodate different reading levels for example, the information contained in the will materials address the same content; content that they think every student has the ability to access, although some may need more guidance than others to develop skills to decode, interpret and apply information found in the readings to do and learn science.

The effects of time constraints on thinking. Teachers described new PCK they developed related to how they think about negotiating time constraints. During interviews, six of the teachers in the sub-group questioned the educational value of
having students complete classroom presentations. These teachers noted it takes two to three days for students to prepare PowerPoint presentations and, in the case of middle-level students, teachers shared that students “spend inordinate amounts of time picking backgrounds and messing with the graphics rather than focusing on the scientific story they are preparing to tell.” A high school teacher repeatedly emphasized the idea during conversations following a final classroom observation and in the focus group that for the most part, each group of students focused on the same ideas in their inquiry and that for this reason, the majority of the audience became bored and essentially “checked-out” after the second or third presentation. Thus, in his opinion, presentations were not a good use of instructional time.

One teacher in the focus group recommended to the rest that they consider doing an alternative summative activity such asking students to post their final projects to the class website. He said that he learned this year that he could increase the level of student engagement and thinking by flipping instruction and having students respond to other groups’ website postings online in preparation for roundtable discussions. Teachers shared during the interviews and focus group discussion that they regularly read the student postings and developed a set of guiding questions for student facilitators to use at each roundtable discussion. They said that their students rotated from roundtable to roundtable where they discussed each inquiry project using the facilitate prompts and a loose guide to get conversations started.

Several teachers in the focus group questioned their colleagues’ idea of flipping the lesson in this way because it assumes all students have access to the Internet from
home. However, during the follow-up discussion, teachers agreed that there are multiple ways in which students could share a written report of their work with images and other groups could respond to these ideas without using an online interface. For example, one teacher offered the idea that “students could do a gallery walk, write responses as homework and come prepared for roundtable discussions the next day.”

Teachers reconsidered lessons that they had decided to write out of their unit due to time constraints. In particular, they frequently cited in interviews the omission of the topic of bio-ethical concerns related to molecular modifications, deciding to add it back to their units next year. A high school biology teacher emphasized:

We could have looked at bio-ethical concerns with nanotechnology, they have been very interested in that topic and I could have had them do some research and reading on that… it’s just time constraints. With the biology, it’s a year of bio squished into a semester and then in the spring is anatomy, so I felt very much like I needed to be careful about what are the central building blocks to prepare for the next units and focus our time on those key topics as much as possible.

However, interviewees agreed that because students were asking for this information, they ended up taking lab time to have lengthy discussions about bio-ethics that were not scheduled into the lessons. In effect, doing so meant less time was spent completing their investigations during the two weeks allotted to the unit. So, making time for this discussion and framing it well with an article to focus the conversation after the SEM is no longer in the classroom is a change teachers say they will make next year.

Creating an annotated databank of photo micrographs. Teachers referred to the large amount of time they and their students spent simply figuring out what type of samples image well with the SEM and which ones do not. Call-out reflections and
comments made during interviews contributed to the on-going conversation within the program about building a catalogue or searchable annotated databank of images of materials that image clearly with little to no electron charging and materials that image poorly due to electron charging with the SEM with annotations regarding how to help students to deeply analyze different types of materials.

For instance, a high school biology and chemistry teacher wrote a call-out that read “on our hair images, frequent charging occurred. [A] drawing of each strand would be a nice addition for this project.” She went on to say when the hair charged, she was surprised because her earlier experiences with imaging hair had been much more successful. She shared that she and her students discussed possible reasons for the charging; for example, the amount of oil or hair product found on the samples and different types of hair from different animals may have more dander or other organic materials that caused charging. During the interview, this teacher added that labeling the drawings and photo micrographs would further assist students to internalize new knowledge and help future users of the database to see important distinguishing characteristics on hair specimens.

This teacher’s comments relate to an instructional goal of identifying variation in materials such as of how quickly hair may charge and a pedagogical goal of asking students to approach learning how to carefully make and communicate observations of hair by both drawing and capturing digital images of samples. This contribution is an important one because teachers are concerned about maximizing student success by selecting materials that image well, facilitating students’ understanding of why particular
materials charge quickly or not and providing multiple approaches to characterizing samples.

Next, I report evidence related to gains in teachers’ scientific content knowledge. Unlike this section that focused primarily on the sub-group of 14 teachers, the following section will report first on the entire group of 23 teachers and then the sub-group of 14 who completed the reflection cycle within the dissertation data collection period.

**Gains in Teachers’ Scientific Content Knowledge**

The last piece of evidence I present in Chapter Four begins with changes to all 23 of the teachers’ metastrategic thinking and PCK. This analysis was based on data from the Project NANO workshop content-based pre and post survey results and the units of instruction; both sources demonstrated that teachers entered the summer workshops with a wide range of background nanoscale content knowledge and technical knowledge related to scanning electron microscopy. I begin with a presentation of the pre and post survey results.

The pre and post survey was administered at the beginning and end of each of the three summer workshops. Each survey was scored immediately so as to inform improvements to the program. Please note, however, that for the purpose of this study, the survey instrument has a limited use in measuring teachers’ scientific content knowledge gains. It can be reasonably argued that the classroom observation data and the teachers’ own words in interviews, written CoRes and call-out reflections and units of instruction are better tools to elicit and capture teachers’ rationales for their instructional choices. However, it is interesting to consider how participants’ survey responses
changed and unit-plans developed as the instructors used the survey responses to calibrate their own instruction and coaching. It is also interesting to note connections between the participants’ awareness level of nanoscale science content prior to the course and the strategies she or he choose to employ. The following data are presented with these ideas in mind.

Recall from Chapter Three that the pre and post survey included four, open-ended response questions for the first of the three summer workshops. The item analysis of the pre and post survey scores for the first workshop revealed that the majority of the participants scored either a one or two of three possible points on questions related to the concepts of size and scale and to a question having to do with materials that cannot be loaded into the SEM. Essentially, the low survey scores indicate that all but five of the 23 teachers were unfamiliar with nanoscale concepts and unfamiliar with affordances and limitations of scanning electron microscopy. In response, the co-instructors added lessons to the following workshops that directly addressed these ideas as well as modeled how to use the microscopes to actively teach these ideas.

To measure whether or not this change in the workshop related to changes in thinking, two multiple-choice questions were added to the survey relating to size and scale and materials such as wet, oily, magnetic or live samples that cannot go into the SEM. In addition, three teachers in the first workshop expressed that words in the survey “the mechanics of the tool” confused them, thus potentially causing construct irrelevant difficulty. Thus the second question on the survey given to participants in the first summer workshop that read, *Describe five key components of the scanning electron...*
microscope (the mechanics of the tool) was changed for the second and third workshop by removing the words mechanics of the tool from this question. Otherwise, the four open-ended response items used in the first workshop survey remained unchanged for the second and third workshop.

As indicated in Table 21, in comparison, the gain scores for the group of participants in the first of the three summer workshops demonstrate that they may have entered the class with a lower level of understanding of basic nanoscale science and technology, whereas each of the two subsequent groups of participants showed higher pre scores and gain scores on the post-test average. It is possible that this lack of prior knowledge may have contributed to the first groups’ lower pre survey scores and higher gain scores overall.

Table 21

Pre and Post Survey Scores for the Entire Group of 23

<table>
<thead>
<tr>
<th></th>
<th>Pre Score Average</th>
<th>Post Score Average</th>
<th>Gains</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td>1.63</td>
<td>2.25</td>
<td>.25</td>
<td>2.75</td>
</tr>
<tr>
<td>Group 2</td>
<td>1.77</td>
<td>2.6</td>
<td>.95</td>
<td>2.61</td>
</tr>
<tr>
<td>Group 3</td>
<td>1.77</td>
<td>2.83</td>
<td>.98</td>
<td>2.75</td>
</tr>
</tbody>
</table>
Nineteen of the 23 teachers demonstrated gains in the post survey in comparison to their pre survey scores. Although none of these 19 teachers had prior experience teaching with nanoscale science and technology, they entered the summer workshop having recently completed the pre-requisite readings and video viewing within the previous two weeks; they also had developed ideas of potential topics and themes to address in their unit and brought samples to examine with the SEM. All of these teachers had some difficulty identifying the meaning of the term *big ideas in nanoscale science* with which to frame their unit and were observed to engage in detailed discussions during the workshop to first figure out how to interpret the meaning of the term big idea and then to select which learning objectives and big ideas in nanoscale science and technology they would use to frame their units.

During the workshops, seven teachers explicitly said to either the co-instructors or to the researcher that they were frustrated and uncomfortable planning their units around three to eight key learning objectives and then backwards planning their unit from there. They indicated the primary source of their discomfort was their uncertainty about the meaning of the big idea construct, but that they also felt filling out the CoRe with their group distracted them from the “real” task of developing a unit of instruction.

Two teachers who expressed their frustration during the workshop later communicated that a week after the workshop, they revisited their CoRe table, and based on their own earlier writings, dramatically re-conceptualized their entire CoRe table and
from there, reworked their units from a new perspective more fully based on their PCK related to student thinking, instructional strategies, their district or school curriculum and the learning objectives they chose to frame their unit around. They enthusiastically reported that they shifted their thinking and began to see the CoRe process as a very useful approach to pre-planning a unit, especially when working with their colleagues. One of these teachers further reported that she contacted her school district science specialist to share how she had used the CoRe to plan her unit and that she highly recommended that the science specialist use Resource Folios to support teachers in authentically implementing the backwards-by-design (Wiggins & McTighe, 2006) planning approach.

Three teachers who scored three of three possible points on the majority of the pre survey items also scored three of three points on most of the items on the post survey. A ceiling effect was observed for each of these teachers, indicating that the survey instrument was not sensitive enough to capture whether or not this group of teachers experienced science content knowledge gains. Each of these three participants are high school teachers (biology, chemistry, physics and engineering respectively) who brought prior experience working with nanoscale science concepts and technology to the workshop. They each reported that they completed the pre-requisite readings and video viewing and entered the summer workshop with well thought-out ideas concerning the learning objectives and big ideas in nanoscale science they would use to frame their unit.

In contrast to many of the participants in the 2012 cohort, these three teachers reported that they were comfortable with the learning objectives construct and felt
prepared to develop the CoRe as part of the planning process. Interestingly, two of these three teachers taught or have taught in school districts that are implementing a proficiency-based education model that draws upon the backwards-by-design (Wiggins & McTighe, 2006) approach to plan units of instruction, thus there is a possibility that this prior experience may have influenced their thinking.

The teachers who scored well on both the pre and post survey did not necessarily complete the CoRe table and plan their units in a linear fashion. Instead, each of these three teachers came to the summer workshop prepared to have conversations with the workshop instructors about the scope and sequence of their units and with ideas for potential instructional strategies to employ in their units. They engaged in iterative, cyclical conversations about how they would sequence the unit within their science courses and wrote in their CoRe tables that they gained ideas about how to scaffold skills and knowledge in the unit. Because they entered the workshop prepared in this way, they communicated in their interviews that they were able to focus the majority of the time in the workshop on “playing with samples to find out what imaged well and thinking about how to guide students through looking at the samples and talking about what they see.”

These three participants wrote part of the units as homework each evening after the summer workshop sessions so that, as one teacher shared during an interview, “my group and the workshop instructors would have something to respond to each morning so we could keep making it a better plan.” Another one of the high scoring teachers added that, “this worked out great because this way the [workshop instructors] knew what to point me to in terms of online resources like videos, activities and even sample units I could
draw upon to build my unit from that starting place, rather than having to start from scratch.”

In contrast to teachers who entered the workshop with little to no awareness of the nanoscale concept, this group of three teachers were observed to be able to take more advantage of collaborating with the experienced workshop instructors and then explore the available resources with specific needs in mind and then test emerging ideas with the microscopes. Those who were less prepared when they entered the workshop were observed to have less time on the instruments and spent up to two more days working with their groups to figure identify their learning objectives and big ideas in nanoscale science for their unit and write their CoRes; they also designed the bulk of their units on the last day of the workshop or after the workshop concluded.

Only one teacher who had a low pre survey score did not significantly improve on the post survey. Interestingly, this teacher exhibited difficulty with designing her unit of instruction, describing the nanoscale with her students and generally felt that she was unsuccessful in teaching her unit. For more information on this teacher’s experience, please refer to Annie’s case in Appendix C.

In summary, teachers expressed a number of changes to their PCK regarding both technical and pedagogical solutions. They reconsidered familiar practices such as forms of summative assessments to develop methods to increase student engagement and the development of students’ higher order thinking skills. Many of the changes to PCK related directly to solutions for challenges posed by working with microscopes, which is
unsurprising given that 10 of the 23 teachers reported on the pre survey that they did not teach using digital instruments prior to joining Project NANO.

A significant number of the changes to thinking that teachers reported transcend the nanoscale unit of instruction and actually inform teaching practices related to integrating any novel science or novel technology into the classroom. Many of the ideas teachers shared reflect the fact that teachers are negotiating the integration of not only new content and technology, but also radically new teaching strategies using a proficiency-based education model. Thus, there is potentially much to be learned here, not only from the perspective of a teacher or PD provider seeking ideas for how to integrate novel science and technology into the secondary curriculum, but also for those interesting in understanding how teachers are drawing upon their metastrategic thinking to develop rationale for how to draw upon their metastrategic thinking and to select from their PCK to frame ideas and facilitate learning for all students.

**Summary**

The 2012 Project NANO cohort of teachers shared a wealth of knowledge based on their metastrategic thinking and PCK. As anyone who has ever taught a new unit of instruction knows, the first year is always a highly experimental year. The structure of Project NANO is purposely designed to assist teachers to develop their own ideas about how to frame their units rather than implementing someone else’s example with fidelity. Although it certainly was the case that teachers drew heavily on the instructional strategies described and modeled by the workshop instructors/coaches, each teacher addressed the challenge of negotiating the inclusion of novel science and novel
technology from a different entry point on a learning progression. Teachers’ positions along a learning progression were dictated by the metastrategic thinking and PCK they brought with them to the Project NANO experience that afforded the capacity to develop a rationale for how to select from the resources offered through the program and from their own resources external to the program to include in their unit of instruction.

Teachers’ own words and actions demonstrated that they successfully established benchmarks to measure and evaluate their own thinking and that of their students as they taught their Project NANO unit for the first time. They responded to their own ideas and that of their students in their call-out reflections and interviews by either affirming that strategies worked well, needed adjustment or in some cases, did not work as intended and needed to be changed. There is much to be learned from these teachers who were brave enough to de-privatize their practice and share their thinking process as it developed.

Regardless of how well prepared teachers were upon entering into the workshop, all of the participants dealt with technical issues during this first year of learning how to work with a scanning electron microscope and research grade optical microscope. Teachers reported that the coaches were invaluable in assisting them with these technical hurdles, which every teacher eventually successfully negotiated to some degree. During interviews and in their call-out reflections that next year, teachers noted that they will have a much clearer sense of where to set up the instruments and other stations, how to use the instruments and how to guide students using formative assessment prompts and probes that inspire students to use high order thinking skills to think critically about their inquiry.
As is to be expected, those who entered the summer workshop with preliminary pedagogical ideas for how they would negotiate the inclusion of nanoscale science and technology were more adept at drawing upon resources provided through the summer workshop and coaching support to develop units of instruction that facilitated the development of higher order thinking skills in comparison to less prepared teachers who spent the majority of the workshop focused on learning nanoscale concepts, how to use the SEM and Leica and choosing learning objectives and big ideas to frame their units. Teachers who were less prepared said that they relied more on the coaches and their colleagues from the workshop to assist them to complete their unit of instruction plan following the workshop. But regardless of where they started in this process, all of the teachers exhibited the use of all of the forms of PCK to negotiate the inclusion of novel science and novel technology into the classroom and used their metastrategic thinking to build upon this PCK to support the development and use of students' higher order thinking in new and interesting ways.

Interestingly, the students themselves had a profound impact on changes to teachers’ thinking. For example, when students prepared too many samples to examine within a 20-minute period, teachers realized the importance of reorganizing lesson plans to allow for students to have time to explore specimens before analyzing samples for specific characteristics and of limiting the number of stub they allow students to prepare. And when students became bored looking at other people’s SEM images on the overhead projector without interpretation, teachers realized that oversaturation of images led to student disengagement. Thus, in this first year teachers reported building upon their PCK
about student thinking that will inform their metastrategic thinking process as they refine their unit for next year.

Finally, what is to be learned from Chapter Four is something about the learning progressions that this particular group of teachers experienced as they met the challenge of negotiating the inclusion of novel science and technology into the science curriculum for the first time. As is the case with any group of learners, the adult students in this group each brought to the experience a unique set of background knowledge and skills that served as limitations and affordances influencing how they thought about their nanoscale science unit of instruction.

Operating within a community of practice, this group of teachers is remarkable in that they each shared ideas that significantly contribute to the field of nanoscale science education and to the body of knowledge concerning how teachers in general think about including novel science and novel technology into the secondary level science curriculum. They are a group of educators who are truly teaching and learning on the leading edge of science education.
CHAPTER FIVE

CONCLUSIONS, DISCUSSION, AND IMPLICATIONS

The primary goal of this research was to describe how 23 secondary level teachers in the 2012 Project NANO cohort drew upon their metastrategic thinking and PCK to negotiate the inclusion of novel science and novel technology into the secondary science curriculum. This dissertation is significant because it is among the first research to describe how teachers draw upon their existing metastrategic thinking to select from their PCK to negotiate the inclusion of nanoscale science and technology into the curriculum.

The study documents practical approaches 23 teachers selected and developed to solve common technical and pedagogical problems of practice that all secondary teachers approaching the integration of nanoscale science will face in this nation, especially teachers in states that adopt the Next Generation Science Standards (Achieve, 2013) which involves a number of nanoscale science related standards. The study also document not-so-common problems of practice that are discipline specific as well as specific to actually working with an SEM in the classroom.

Another reason that this study is significant is that it utilizes an established approach to teacher professional development known as Research Folios, in a novel way to conduct a descriptive case study of teachers working with novel concepts and technology. Thus, a major outcome of this study is the generation of a design-based research model useful to elicit and capture teachers’ thinking as they navigate development of a nanoscale concepts and technology unit of instruction. Furthermore,
the use of this research model is not limited to nanoscale science and technology, but could be applied to elicit and capture teacher thinking about the inclusion of any novel content and technology in science. Another important outcome of this study is the generation of four Resource Folios that provide both general and topic-specific examples of how a small number of middle-level and high school teachers drew upon their metastrategic thinking and PCK to integrate novel concepts with previously known science content using high powered microscopes to enhance student learning.

This chapter begins by addressing the study’s guiding research questions with a summary and conclusions that can be drawn from the study as teachers drew upon the supports provided through Project NANO, science standards and their own metastrategic thinking and PCK to plan, implement and reflect on their nanoscale science unit. Next, a discussion of the limits of this study pays particular attention to the research methodologies used in this study.

The chapter then provides a discussion about implications of this study for Project NANO and for programming for teacher education and professional development for practicing teachers. The section broadly addresses policy, practice, and leadership, and recommendations for future research. Finally, the chapter concludes with some personal reflections related to who I have become as an educational leader as a result of this dissertation process and how this study relates to the fulfillment of my original motivations for entering the Educational Leadership doctoral program.
Summary and Conclusions

A variety of themes were developed from the data, illuminating teachers’ metastrategic thinking and responding to the overarching how do teacher participants in the 2012 Project Nanoscience and Nanotechnology Outreach (NANO) program negotiate the inclusion of novel science and novel technology into the science curriculum?

Summary of results: metastrategic thinking. Teachers applied their metastrategic thinking to establish the scope and sequence of the unit and then drew and built upon their PCK to identify specific approaches used to organize key learning objectives, select and implement learning activities, measure student’s responses and respond to student assessment data.

As teachers considered the scope of their units, they first focused on affordances and limitations of scientific tools, big idea in nanoscale science and a small number of key learning objectives for their unit. Drawing on best practices in science education and state science content standards, teachers considered how to frame a scientific inquiry experience for their students in a way that they thought would maximize student engagement and suit each classes’ developmental needs, serve to debunk students’ misconceptions in science, and provide student with practice developing skills and integrating new science content knowledge within their existing body of knowledge. They sought to assuage their own anxiety and that of their students by incorporating familiar technologies and teaching strategies into the unit to complement the inquiry experience.
For example, teachers included station activities that involved the use of complementary technology such as informational videos on nanoscale concepts and applications, Excel to create data spreadsheets, Vernier scientific probes and analytical software, and analogue instruments such as hand-lenses and optical dissecting microscopes that students used in earlier inquiry lessons. Teachers also considered which topics were to be included in the unit and which were outside of the scope of the unit based on time constraints, their ideas about developmental appropriateness and how they wished to sequence the unit activities within the greater cycle of the entire course.

In the context of determining the scope and, later, the sequence of the unit, teachers considered so-called “big ideas” in nanoscale science and technology. Analysis related to the research sub question of the nine “big ideas” in nanoscale science and technology, which are the big ideas that teachers choose to teach in their Project NANO unit and why?, indicated that all of the teachers involved three of the big ideas in nanoscale science in their units as a central organizing framework. They used the big ideas of tools and instrumentation, size and scale and the structure of matter. The big ideas of science, technology and society and forces and interaction were employed by 56% of the teacher; 40% of the teachers integrated size-dependent properties, as well as models and simulations, but only 13% of the teachers incorporated the big idea of quantum effects. However, none directly addressed the big idea of self-assembly.

Teachers provided a range of descriptions for why they chose to involve these three big ideas structure of matter, size and scale and instruments and tools including; the emphasis of the Project NANO program, the availability of the SEM and Leica to
visually analyze and measure samples and the opportunity to approach difficult and fundamental topics in science to learn about interdisciplinary topics from multiple perspectives involving kinesthetic, audio and visual learning modalities.

Teachers also described their rationale for which big ideas to include and which to leave out of this particular two-week unit as they developed the scope and sequence of the unit within the greater science course. For example, teachers described how the unit logically connects and builds upon prior knowledge and prepares students for learning increasingly complex concepts and processes. Participants also described changes to the scope and sequence of the unit and in their thinking in response to their own experiences learning new content and technology. Throughout the entire experience, teachers couched many of their ideas in response to their understanding of how students thought about the nanoscale concepts and related ideas.

**Summary of results: pedagogical content knowledge (PCK).** Based on their view of the nature of teaching and learning science for students, participants drew on their PCK to select and scaffold activities they decided would be most useful for supporting the development of students’ knowledge and skills. They drew on their PCK to determine the structure of the classroom organization for each lesson, which involved a small amount of direct instruction combined with laboratory activities. Thus, students spent the majority of class time conducting scientific inquiries. Teachers drew on their PCK to decide how many stations to have, the nature of the content addressed in each activity station and the organization of groups of students to maximize student engagement and learning.
Due to the nature of Project NANO, all of the teachers shared a great deal about the PCK they drew and built upon to negotiate technical problems and solutions ranging from learning how to select, prepare, and mount SEM samples with students to learning how to operate the instruments and teach others how to use the SEM to capture quality images. Teachers also improved upon use of consistent technical language to guide students through the process of examining and characterizing specimens using higher order thinking skills.

All of the teachers reported that coaching support for resolving technical issues and assistance with problem solving pedagogical concerns was instrumental to their success as they formed the foundation of their nanoscale-science-and-technology-specific PCK this year. For example, given the significant gap of time between the summer workshop and the implementation of their units, teachers needed to be reminded how to use the SEM controls, what type of materials can and cannot be loaded into each instrument, how to focus using the Leica microscope lens and how to save and manipulate images captured with either of the two microscopes. This on-going coaching support made a critical difference between the units participants developed in the summer actually being implemented in the classroom or not and instructional theories and methods learned through the workshop actually becoming integrated into practice or not.

All of the teachers who completed their implementation and reflection cycle during the data collection period \( N = 14 \) of 23 teachers) emphasized the need to have well-prepared adult volunteers assist in the classroom next year to improve the teachers’ ability to teach science as guided or open inquiry, improve volunteers success in assisting
students and to improve students’ overall level of academic achievement. Teachers who
did involve adult volunteers offered ideas for how to prepare volunteers in advance such
as providing volunteers with a schedule of activities in advance of the unit, providing
volunteers with readings and links to informational videos on the scientific content that
will be addressed in the unit, and walking volunteers through each activity station and
demonstrating how to facilitate students’ use of technology at each station. This advice
served to inform the work of teachers who implemented their units later in the year and
will inform future cohorts of Project NANO teacher participants.

Finally, the last key themes related to teachers’ PCK are student assessment and
differentiation of instruction. Student assessments also influenced teachers’ sense of how
to calibrate the inquiry process for learners. More experienced teachers shared ideas that
influenced shifts to their instructional moves during class while novice teacher and those
less confident working with the nanoscale concept and technology reported that most of
their reflection and responses to student assessment data took place between classes and
influenced what they did the next day or will influence changes to the unit for next year.

All of the units employed the use of formative assessments intended to inform
students about their own thinking and progress and inform teachers’ moves. However,
teachers report frustration at being stationed near the SEM most of the time and unable to
assist students at the activity stations other than the SEM and Leica station. Particularly
the novice and mid-career teachers and those working with younger students shared that
without the opportunity to interact with students and guide their thinking, teachers felt
less able to understand what cognitive and even physical barriers to learning existed and
why some students were less engaged than others throughout the lessons. As a consequence, although all of the units explicitly involved activities designed to appeal to a variety of learning styles using audio, verbal, visual and kinesthetic teaching and learning modalities, teachers expressed that they lacked the flexibility to utilize differentiation strategies they would employ in a more normal situation where they would be able to circulate among students asking guiding questions, facilitating activities that require students to pause throughout their inquiry to share and check their thinking and then calibrating their own responses based on their observations and interpretation of student thinking.

**Summary of results: changes to teachers’ thinking.** Given that this was literally the first time any of the participants had developed or taught a nanoscale science or engineering unit of instruction, each teacher expressed or demonstrated a number of changes in their thinking. These changes related both to teachers’ metastrategic thinking and PCK and to scientific content knowledge gains.

Examples of changes in teachers’ thinking inform the sub question, *how, if at all, do teachers’ metastrategic thinking and PCK change between the summer workshop and the reflection period following the implementation of the Project NANO unit?* Changes in teachers’ thinking included growth in scientific knowledge, technical knowledge and changes to PCK. Nearly every teacher demonstrated growth in terms of their understanding of the nano concept and every teacher learned how to use the Phenom SEM with students pursuing topic-specific inquiries.
The entire sub-group of teachers who completed the unit during the data collection period emphasized changes in their thinking about how to organize stations and groups of students and for how to re-organize the order of presentation of materials and educational experiences. The sub-group of teachers also described their ideas for how to draw on assessment tools in new ways next year to better facilitate the development of students’ higher order thinking skills and to improve upon the integration of scientific knowledge and skills.

Teachers in two different feeder school groups and one sixth through high school private school are thinking more expansively as a result of working with Project NANO. Rather than considering how to scaffold learning experiences in just one grade level, they are discussing how they plan to sequence nanoscale science experiences through the middle-level and high school science courses. Teachers described meetings that took place over this academic year to plan how to sequence nanoscale science and engineering units throughout the secondary level to ensure that students do not receive redundant instruction and instead experience instruction that intentionally scaffolds knowledge and skills approaching increasingly sophisticated topics in science and in engineering design.

The study also demonstrated that all of the teachers in the cohort gained scientific content knowledge. This evidence informs the sub question, do teachers demonstrate scientific content knowledge gains in response to the 2012 Project NANO summer workshop?

Eighteen of the 23 participants demonstrated content knowledge gains on the pre and post survey, three experienced a ceiling effect and maintained high pre and post
scores, and one teacher did not demonstrate statistically significant gains on the post survey. However, despite indications provided by the pre and post survey results, all of the teachers, even the four who demonstrated little to no gain on the post survey, spoke about content knowledge gains they felt they had made as a result of their involvement in Project NANO this year. Although three teachers had worked with electron microscopy in either a professional application or as a graduate research assistant in a laboratory application, none had used the Phenom tabletop Scanning Electron Microscope. All of the teachers learned something about how an SEM works in comparison to other types of electron microscopes and all learned how to work the specific controls on the Phenom SEM. All of the teachers learned what materials can and cannot safely be loaded into the particular model of SEM they were using and how to prepare sample stubs to load into the Phenom.

In summary, all of the teachers in the cohort demonstrated and specifically addressed changes in their thinking that will inform improvements not only to their nanoscale unit, but also new ideas that built their PCK related to teaching and learning other units of instruction that involve novel science and technology. These new ideas are useful to their own practice and thanks to the participants’ willingness to share what they learned, they will serve to support the efforts of many others who share their position learning on the leading edge of science education.

Conclusions. Teachers drew upon and built their metastrategic thinking and PCK to develop inquiry-based units to navigate the inclusion of novel science and technology into the curriculum. Evidence of teachers’ thinking demonstrated that there is more than
one effective way to approach common problems of practice related to integrating novel science and technology into secondary science curriculum. Teachers demonstrated multiple ways of employing metastrategic thinking to draw upon and build PCK used to negotiate significant challenges such as how to structure opportunities for learning that engage diverse learners’ higher order thinking skills and how to manage authentic inquiry experiences with larger-than-usual class sizes. Based on this experience of working as members of a community of practice, teachers learned new ways of thinking about not only how to integrate nanoscale science and technology into the science curriculum, but also gained new ideas for how to integrate other novel science and technology into their classrooms as well.

This study contributes to the development of baseline knowledge regarding teachers’ multiple entry points along a learning progression to design a topic-specific nanoscale unit of instruction. With the exception of one teacher, each participant designed and implemented developmentally appropriate scientific inquiry-based units of instruction. The research methodologies employed in this study proved to be useful for supporting the development and communication of teacher’s metastrategic thinking and PCK throughout the experience. That said the following section addresses possible limitations or errors worth consideration.

Limits of This Study: Sources of Potential Error

Every day, I walk past a linguist’s office door where I see Magritte’s famous image with the caption “Ceci n’est pas une pipe,” French for “This is not a pipe” (see Figure 14).
This piece of art reminds us that words and classroom observations have limited capacities to capture the full story of teachers’ metacognitive thinking and the forms of PCK teachers drew and built upon as they negotiated the inclusion of novel science content and novel technology into the curriculum. Although I believe that the structure of the Project NANO workshop and this research design have shown to be very promising in stimulating reflection and eliciting representations of teacher’s thinking, it is important to note that a critical reflective process is not a linear experience, but rather a continuous building and unfolding of awareness of how to integrate multiple ways of knowing how to teach.

I invite the reader of this research to keep in mind the fact that this study examined and described teachers’ thinking during a period of their first exposure to the process of developing ideas for how to integrate nanoscale science and technology into secondary science curriculum. Furthermore, the descriptions of teachers’ thinking provided in these pages are representatives of forms of teachers’ PCK that they said that
they drew upon or that I observed. Although it is true that each of the forms of PCK represented here provide a glimpse of the complexity of teachers’ thinking, many nuances of thinking are missing from the descriptions provided in this dissertation.

This study asked teachers to shift their thinking to make explicit ideas they are not normally asked to share, such as expressing vulnerability about a lack of scientific knowledge and describing their rationales for how they frame questions or withhold comment in specific moments of students’ process of discovery. It is important to note that making this change to think and communicate in new ways about one’s teaching practice is an iterative process as well, and not one (in my experience) that all teachers are excited or even willing to fully engage in no matter what the stated benefits may be. Plus, teachers repeatedly pointed out that it takes them at least three times teaching a new unit before they feel that they truly gain a strong grasp of how to adapt the unit to coherently fit into the scope and sequence of their class and to understand how to adjust the lessons to respond to students’ thinking, let alone figure out how to communicate their new PCK as it emerges. It was apparent in this research that some teachers were certainly more eager than others to share their ideas. Furthermore, all of the participants recognized that they had only begun to conceptualize how students thought about nanoscale science and technology, thus there is much more of this story left to be told than what is detailed in this research.

Another possible limitation to this study is the fact that I played a dual role as both the internal program evaluator and a dissertation researcher. It is certainly true that my role as an integral member of the Project NANO tool provided a number of
affordances in terms of credibility with the teachers and other staff members and opportunities to deeply collaborate with the team to develop, pilot and ultimately conduct the final dissertation research. However, this dual position reduced my ability to serve as a totally unbiased, third party investigator. Given my history with the program and at least half of the teacher participants whom I’ve had the pleasure of working with on several projects over the past five years, my attention was attuned to be sensitive towards certain issues I learned about prior to beginning this dissertation research.

For example, in response to situations I noticed when testing out various classroom observation protocols during the pilot phase of this study, my attention became highly attuned to look for possible effects on the inquiry process to have the teacher essentially rooted to a fixed location while students’ navigated the rest of the inquiry in a largely independent manner. Similarly, teachers who knew me and my background and were mindful of conversations we have had in the past may have tailored their responses to me in ways that may have been different had someone they did not know at all served as the evaluator or researcher.

There is a possibility that had I been partnered as a dissertation researcher working with an external evaluator, my attention may have been attuned in different ways that may have afforded differences in the way I interpreted situations and teachers’ meaning. As I have said elsewhere in this dissertation, I believe that using multiple measures and triangulating data, establishing inter-rater reliability on instruments such as the scoring guide and rubric and also relying on my advisors and cohort members to hold
up potential biases served to mitigate such potential biases or limitations. Nonetheless, all of the potential limitations I have mentioned here are worth consideration.

There are two additional important considerations related to potential sources of error in this study. The first relates to the fact that only 14 of the 23 participants completed the full implementation and reflection cycle by the end of the data collection period. Although the study did not intend to include the remaining nine teachers, the results of the research may have been impacted by the fact that the perspectives of the teachers who taught the units in the spring were not represented in portions of the study related to teachers’ reflections on their experience teaching their nanoscale unit of instruction.

Interestingly, 11 of the 14 teachers in the sub-group teach at the middle-level. Thus, many of the ideas in Chapter Four, especially ideas in the section related to changes in teachers’ thinking, could be specific to middle-level PCK. Although many of the technical challenges teachers faced were certainly similar regardless of the grade level they were teaching, the pedagogical challenges were distinct for middle-level and high school level teachers. So although it is not necessarily a source of error that this study provides more descriptions for changes in thinking for middle-level teachers’ than high school teachers’ thinking, it is important that those who read this study contemplate developmental levels and students’ learning progressions when considering the implications of the findings reported in these pages.

For example, the bulk of a middle-level science teachers’ practice was focused on introducing students to fundamentally new ways of thinking about the natural and built
environment. Teachers at the middle-level were largely focused on introducing scientific content and scientific procedures to children, many of whom may have never experienced formal science instruction prior to middle school. Middle-level teachers were also working with students who are, for the most part, used to fairly constant guidance to navigate academic subjects. Thus, inquiry-based experiences that require a significant amount of independent work to decode instructions and otherwise think critically and problem-solve on their own would have been new experiences for many students.

Although it is true that students at all levels of education are constantly being exposed to new vocabulary, middle-level science requires that students apply language to negotiate meaning in a way that is new to most students. By high school, many students are more adept with scientific procedures and scientific language used to make meaning in situations involving ill-defined problems. Thus, the forms of PCK teachers bring to bear must be both content specific and developmentally appropriate for learners.

The second significant limitation to this study is the simple fact that I narrowed the field of view as a researcher to examining teachers’ thinking almost exclusively. Obviously because I conducted classroom observations and watched how teachers and students interacted with one another, the content and the scientific instruments, students were not completely ignored. However, I observed in only seven of 23 classrooms and my primarily focus during these classroom observations was not on student responses but rather on each teacher’s PCK that informed their responses to student thinking. There is a strong possibility that if I had examined both the teachers’ and the students’ thinking, I
may have been able to tell a more nuanced story with this study than I am able to do as it stands.

Instrument validity is another potential source of error in this study. Here I name potential sources of error for each instrument used in this study beginning with the EQUIP classroom observation protocol.

**EQUIP.** The EQUIP classroom observation protocol was used to conduct classroom observations in Project NANO teachers’ classrooms. The EQUIP is a tremendously useful tool for focusing the attention of the researcher on fundamental aspects of science teaching and learning within an inquiry-based context; however, the instrument was not specifically designed to detect forms of teachers’ PCK.

I drew extensively on fieldnotes throughout the data analysis period. Although these fieldnotes were highly descriptive in nature, the description was based on my sense of how to interpret teacher participants’ moves within the framework of EQUIP and my own orientation as a science educator. As a non-participant classroom observer, I did not ask teachers about their thinking in the moment, although teachers did at times offer their thoughts without solicitation during class. Some of teachers’ rationales for instructional moves were either based on tacit knowledge which is difficult to describe, especially after the fact, or had been forgotten by the time teachers shared their thinking after class or in call-out reflections. It is also possible that some of the moves were unexamined by the teachers, thus they were unable to share reflections on their rationales. In some cases, I was limited to simply describing the moves themselves and not the teachers’
metastrategic thinking to develop rationales that informed their choices for how to draw on their PCK to make instructional decisions.

One particular aspect of the instrument itself also limited my ability to accurately record teachers’ PCK, thus causing me to rely on fieldnotes to capture nuances the instrument was not sensitive enough to catch. The protocol asks the researcher to note the level of student engagement in the classroom every five minutes throughout the observation. The observation protocol also allows for only one number to be entered in the data log under each of four categories of observation; it is often difficult to choose just one number to enter for the student engagement category when individual and groups of students exhibited multiple levels of engagement and the teacher was drawing on different types of PCK to address the unique needs of each group, thus student responses varied. In addition, each observation took place at different times within the cycle of the unit, so variation in the level of scores between observations was to be expected.

The last page of the EQUIP provides an observation summary with the following written guidance: “score for each component should be an integer from 1-4 that corresponds with the appropriate level of inquiry. Scores should reflect the essence of the lesson relative to that component, so they need not be an exact average of all sub-scores in a category” (Marshall et al., 2009, p. 9). Because the point of the observation was to derive the essence of the inquiry, the protocol was a useful qualitative instrument in the sense that it enables the observer to assign descriptors that characterize the position of a lesson and ultimately a unit of instruction on a continuum from highly prescriptive to open-ended inquiry. However, it is quite possible that an observer with a different
orientation to science teaching could chose different sets of descriptors from the protocol choices to characterize the observed lessons. The same can be said of any classroom observation instrument. Thus, I believe that this instrument was useful for the purpose it was intended to be used for in this study.

**Pre and post survey instrument.** The pre and post survey was designed to collect a limited snapshot of teachers’ background knowledge related to the nanoscale concept and the SEM. This brief survey was not intended to serve as an exhaustive test of all that teachers know, but rather was intended to inform some general calibration of the summer workshop lessons to each of the groups of participants in each of the three summer workshops.

The survey was locally developed by the three workshop instructors and the researcher and is not a validated instrument. During the first workshop, the workshop instructors received questions from three teachers about the wording of one of the survey items (“the mechanics of the tool”); thus, these words were removed from the survey for the second and third workshop to avoid further construct validity and reliability issues.

Because this research was a design-based study, the instrument was also changed between the first and second workshop when the instructors and researcher noticed that the participants in the first group scored poorly on questions to do with the concepts of size and scale and the SEM itself. The instructors adjusted their instruction to add lessons on size and scale and on the SEM itself and added two multiple choice questions to measure the impacts of their instruction in the post survey. Thus, the instrument was not consistent throughout each of the three workshops; however, the reported data clearly
distinguished the difference between the two forms of the instrument and the results from each survey.

**The unit of instruction scoring guide.** This instrument is another example of a tool designed as an instructional element of the Project NANO professional development program that was adapted for use in the research. The scoring guide is a locally developed non-validated instrument that reflects the values of the program and is biased towards favoring guided and open-inquiry experiences. The scoring guide is also biased towards the production of student work samples as evidence of learning. However, the unit planning template involves open-ended responses in the categories of knowledge and concepts, science inquiry and engineering design, student experiences, learning community, and assessment of student achievement. Teachers’ clearly articulated metastrategic thinking in all of these categories and showed no evidence that their thinking was substantially limited to fit the implicit bias of the scoring guide.

Teachers’ own words provided rich and thick descriptions of their metastrategic thinking and PCK. Participants’ Content Representation tables combined with their units of instruction communicated initial rationales used to make and assess their choices related to modes of inquiry and assessment prior to implementation of the units. The quantitative data generated with the scoring guide used to assess the units of instruction combined with the CoRe codes served to draw attention to thematic patterns within the group or subsets of teacher participants. Detecting these patterns assisted with the development of the broader interpretation of the stories being told. Used in this way, the instrument served as a helpful tool for eliciting teachers’ thinking; however, if the
numerical scores given to the unit of instruction were to be applied without triangulating additional qualitative data, those numbers alone could be potentially misleading.

**Content Representations (CoRe) table.** The CoRe table and unit planning template that provided structure to the planning and communication process may have also limited the range of teachers’ thinking to particular topics and approaches. It was evident that the short duration of time available to learn to use the SEM and Leica functions, test samples and develop the unit placed stress on teachers, some of whom who viewed the CoRe exercise as an unfamiliar and even unnecessary planning step. Every teacher completed the CoRe either during or after the workshop, though somewhat reluctantly in some cases, which may have influenced their responses. Cells left blank on the CoRe table sometimes hinted at a lack of ideas related to specific planning elements such as assessment plans and ideas for differentiation of instruction; however, in some cases teachers chose not to fill out the entire table simply because they didn’t want to spend the time and energy. Thus, signals such as cells left blank on the table required careful interpretation that could be attempted only after collecting additional data to understand whether or not blank cells meant anything of importance to inform the research questions. In some cases, blank cells drew my attention to important elements of teachers PCK worth further investigation but in other cases a blank cell was meant to mean nothing more than a lack of willingness to share ideas.

The CoRe tables and units of instruction were both used to inform the development of the interview questions. Missing or incomplete responses in both sets of teachers’ writing may have led the researcher to frame questions that emphasized ideas
that weren’t necessarily the most pertinent to the teachers’ thinking about how they negotiated the inclusion of novel content and technology into the curriculum.

Teachers were asked to review their CoRes and call-out reflections just before the interviews; therefore, teachers’ interview responses may have been focused more on responding to the earlier writings than on what they learned throughout the implementation and reflection cycle. However, the open-ended nature of the focus group conversation was intended to facilitate discussion to elicit thinking about the applications of PCK and ideas for improvement to their units. Thus, the focus group approach may have balanced the limitations presented by the CoRe itself and the questions asked or not asked during the interview.

**Limits of the coding process.** The CoRe tables, call-out reflections and interview transcripts were first open-coded, and then focus-coded to develop categories of thinking and thematic patterns from the teachers’ own words. As a novice researcher who is also not an expert in every discipline of science taught at the secondary level, my ability to interpret meaning is limited. I may have misinterpreted the level of significance of ideas expressed by teachers because more than one teacher happened to mention an idea, thus amplifying the signal in the data more or less than teachers’ actually meant. I may have deemphasized a topic specific reference because I did not know about student thinking concerning particular concepts and processes. Moreover, I may have reduced the categories of responses beyond the level necessary to share all of what teachers intended to tell about their thinking.
Discussion

Despite the limitations of this study, such as the decision to not include student thinking in response to teachers' instructional choices, there is much to be learned here. For instance, this dissertation provides an example of the use of the Resource Folios approach as a supportive tool to elicit teachers' metastrategic thinking and PCK in such a way that informs teachers' own reflective processes and the coaching partnership with the Project NANO team. This study also offers tangible ideas that teacher professional development leaders and teachers may draw upon to understand the rationales this group of teachers applied to negotiate technical challenges related to teaching with the SEM and Leica. Furthermore, this work demonstrates this particular group of teachers' entry points of PCK along a learning progression as they negotiated the inclusion of the nanoscale concept and technology into the science curriculum.

More generally in this section, I describe ways in which this study contributes to and complements the bodies of research that informed it. First, I begin with a commentary on how the use of the metastrategic thinking and PCK conceptual frameworks supported learning about teacher thinking and their learning progressions as they negotiated the inclusion of novel content and technology into curriculum. In this context, I also describe some potential limitations to the particular definitions of these constructs for this study. Second, I describe how this study was situated within the bodies of literature that informed it. Third, I conclude the section with a final synthesis of the study’s overarching meaning.
Metastrategic thinking and pedagogical content knowledge as useful frameworks in tandem. The combination of the metastrategic thinking and the PCK frameworks provided a powerful and practical conceptual lens to focus on how teachers thought about creating learning opportunities designed to facilitate the development and use of students’ higher order thinking skills while learning new science content and procedural skills. Because an important focus of Project NANO is to support teachers to design inquiry-based units that involve analyzing, characterizing and if appropriate, categorizing specimens, the Project NANO team was interested in understanding more about teachers’ rationales for the choices they made to structure their units. Applying Shulman’s (1986;1987) definition of PCK (knowledge of content, curriculum, student thinking, instructional strategies and assessment) as part of the summer workshop discussions and unit planning activities established a common understanding among the program partners, participants and researcher for how to describe thinking that informs instructional choices. By explicitly adding the refinement of the metastrategic thinking lens as a complement to the examination of forms of PCK, teachers were supported to individually and collaboratively surface and then define specific aspects of their thinking or forms of PCK. Metastrategic thinking informed the development of their rationales for how to structure the learning experiences to develop students’ higher order thinking skills. Applying the metastrategic thinking and PCK lens in concert afforded the opportunity for teachers to consider some of the most fundamental questions related to teaching and learning as part of their planning processes and to relate a more nuanced story to describe not simply what they did but also what they knew about the content and
student thinking that informed their choices of instructional strategies and how their own learning progressed as a result of this experience.

The research sub question, *how, if at all, do teachers’ metastrategic thinking and PCK change between the summer workshop and the reflection period following the implementation of the Project NANO unit?* provided the opportunity for the researcher to work with teachers to apply the metastrategic lens and PCK framework to explore teachers’ learning progressions within a relatively short period of time. Recall that the construct of learning progressions characterizes progress in learning as: “continuous and coherent, an incremental sequence from novice to expert performance, and mediated by instruction” (Heritage, 2008, p.4).

Recently there has been growing interest in this theoretically driven pedagogical approach that emphasizes the learning of big ideas and scientific practices in domains of science over extended periods of time. While the majority of this small but growing body of literature is primarily concerned with how students learn, this study and others like it demonstrate that this construct proved to be quite helpful for interpreting teachers’ thinking and how their thinking changes in response to learning new content and technology and observing how students respond to new instructional strategies. Heritage (2008) points out that, “a well-constructed learning progression presents a number of opportunities to teachers for instructional planning” (p. 5). Schneider and Plasman (2011) have also pointed out:

To think of learning as a continuous or developmental process is not entirely new (e.g., see spiral curriculum [Bruner, 1960] or developmental corridors [Brown & Campione, 1994]). What is more recent is an emphasis on linking instructional
planning and formative assessment in a progression of learning (Heritage, 2008). For teachers, assessment of what beginning and advanced teachers should know and be able to do is at the forefront of discussion of teacher quality (e.g., see National Science Teachers Association standards for beginning teachers [National Science Teachers Association, 2003] and National Board standards for advanced teachers [National Board for Professional Teaching Standards, 2003]).

That said, Shavelson (2009) and Heritage (2008) both cautioned against setting specific goals such as outcome targets for teachers who are learning to teach specific topics. In keeping with Shavelson’s and Heritage’s ideas, I have taken the perspective in this research that it is more helpful to think of learning progressions as development leading to a sophisticated level of expertise rather than a series of discrete events or stages.

Although the purpose of this study was not to examine teacher participants’ learning progressions, but rather to provide a broad description of teachers’ thinking, it is interesting to note ways in which teachers’ background knowledge in teaching science and background in nanoscale science and technology deeply impacted their thinking throughout the cycle of unit planning, implementation and reflection. Although this study does not provide an exhaustive analysis of each participant’s entry point along some sort of a learning progression map, it does contribute to the field some amount of baseline knowledge concerning what teachers chose to highlight as their metastrategic thinking and PCK; how they built upon their prior knowledge and how they thought about integrating new knowledge and skills into their practices throughout this first experience teaching nanoscale science with an SEM.
**Possible limits of the constructs as defined.** PCK is domain and topic specific knowledge of teaching; teachers draw upon what they know about their subject matter to make it accessible to students (Carter, 1990). Therefore, it makes sense that Project NANO teachers experienced changes in thinking as they developed their own understandings of the nanoscale concept, practiced integrating new ideas and experiences into the curriculum and reflected on how they and their students thought about the interrelated concepts and affordances of technology. That said, both the PCK and the metastrategic thinking frameworks, especially the way in which I chose to operationalize these constructs, do have some limitations. For example, I purposely chose not to draw upon interpretations of PCK that go beyond the elements described by Shulman (1986, 1987) and by Magnusson, Krajcik and Borko (1999). In doing so I ignored some very real pressures on teachers’ thinking such as social pressures related to state testing and pressures coming from families to teach certain ideas using specific strategies.

I chose to limit the definition of PCK in this way based on the concern that the use of the term PCK has come to encompass in the minds of many scholars and educators virtually everything teachers think and believe about how to teach. I strongly believe that opening up the construct so broadly dilutes the usefulness of the framework for research. While my steadfast commitment to remain focused on teachers’ knowledge of curriculum, content, instructional strategies, student thinking and assessment certainly refined my focus is useful ways, it could be reasonably argued that this interpretation of the PCK construct limited my ability to notice, interpret and describe elements of
teachers’ thinking that may in fact be useful for teacher professional developers and for teachers to know.

Similarly, my narrow interpretation of the metastrategic knowledge construct that inspired my use of the metastrategic thinking framework may have caused me to miss critical nuances of teachers’ rationales for how they structured learning. Because metastrategic knowledge refers specifically to teachers’ knowledge about how to facilitate learning opportunities for students to build higher order thinking skills, I have missed important elements of teachers’ thinking related to fundamental elements of teaching such as supporting students’ memorization of formulas, algorithms and scientific vocabulary useful for doing and communicating about science.

Although certain mental functions such as memorization and recitation are considered to require lower order thinking skills, they are obviously critical to one’s ability to build towards engaging in activities that require high order thinking. This piece of research captured some of the ways in which this group of teachers scaffolded learning experience to include opportunities for using and developing both lower and high order thinking; however due to the way I framed the discussion with teachers using the metastrategic thinking and PCK constructs, teachers prioritized sharing their reflections on activities that eventually did afford opportunities for higher order thinking.

**Situating the results vis à vis related scholarship.** There is also much to be learned here concerning this study’s contributions to several bodies of literature that informed this work. These areas of scholarship include the small but emerging body of literature related to nanoscale science education at the secondary level, the technical
pedagogical content knowledge literature, and the literature related to PCK, metastrategic knowledge and learning progressions.

This dissertation study adds to and complements in a number of ways several of the studies generated by the NSF funded National Center for Learning and Teaching in Nanoscale Science and Engineering (NCLT), where much of the research in the U.S. on nanoscale science professional development for science teachers has been and is being conducted. For example, although related to Hutchinson’s (2009) study of secondary teachers integrating nanoscience into their current curricula as well as their development of PCK in NCLT workshops, this dissertation study moves beyond Hutchinson’s research by adding knowledge about how teachers thought about and reflected on facilitating students when actually using an electron microscope and optical microscope to explore concepts in science. Thus, this study builds upon Hutchinson’s description of teachers’ PCK as they negotiated teaching nanoscale science content by examining a similar sized group of teachers who have the added experience of using nanotechnology.

This study also complements the existing body of nanoscale science education literature by adding nuances related to teachers’ thinking for how to structure nanoscale learning experiences for specific grade levels and topics by demonstrating how involving students in using the SEM and Leica expands teachers’ ideas for which big ideas in nanoscale science are approachable within a one-to-three week nanoscale science and technology unit. Interestingly, similar to the findings of Stevens, Sutherland, Schank and Krajcik (2007) and Bryan, Daly, Hutchinson, Sederberg, Bernaissa, and Giodanaro (2007), as well as Hutchinson, Daly and Bryan (2009), in this dissertation study, 18 of 21
units were written as extensions and all of the units included the big idea of size and scale. However, with the addition of the personal SEM experience, all of the Project NANO units also involved structure of matter and tools and instruction as key big ideas used to frame the units. Thus, despite the significant differences between the experiences of Project NANO teachers and NCLT teachers, it is intriguing to note similar entry points along a learning progression as teachers all negotiate common problems of practice and challenges posed by the involvement of novel technology and concepts as they designed units.

Finally, the use of the Resource Folios approach in this dissertation research deepens the usefulness of the approach as well as contributes to and complements the existing body of literature concerning PCK. John Loughran (personal conversation, April 28, 2013) pointed out that current PCK research and, indeed, Resource Folios research to date focuses on the most common problems of practice that teachers experience. This dissertation study adds to the literature descriptions of teachers’ metastrategic thinking and PCK to negotiate both common problems of practice and problems unique to working with nanoscale concepts and technology at the secondary level. Given the increased emphasis on nanoscale concepts and technology in the Next Generation Science Standards in the U.S. and in content standards in other countries such as Australia, this description of how teachers designed their units, why they made the instructional choices they made and how their learning progressed as a result of this experience is a valuable resource for professional development leaders and teachers alike.
To conclude, the various voices represented in this study demonstrate that teachers do not progress in a linear manner as they figure out new and better ways to organize learning experiences, but rather teachers draw and build upon their forms of knowledge in a variety of ways. As a result of this study, I have learned that it may be more useful to take a systems-based approach rather than a linear approach to describing how teachers think and how their learning progresses. In this study, I chose methods that provided the opportunity to examine and describe teachers' thinking in a fairly linear manner. As a result of conducting this study, I now believe that choosing alternative instruments that provide a description of a connected network of ideas, rather than attempting to describe levels of thinking, may more accurately describe teachers' learning progressions. Based upon this experience and reflection, I now posit that taking a systems-based approach to identifying which forms of support provide helpful connections in the minds of teachers to rapidly foster their learning about how to teach specific topics using technology may reduce the implementation dip as the new science standards are incorporated into instruction.

Synthesis. This last segment of the Discussion endeavors to make a final offering of the big picture that has resulted from this study and its report. I submit that two “big ideas” are to be gleaned from this dissertation research.

#1 Pedagogical approaches and technical solutions. The first big idea to take away from reading this dissertation is the set of pedagogical approaches for negotiating the inclusion of nanoscience content and the series of technical solutions that teachers shared for working with nanoscale technology and other digital instruments. These
approaches and solutions comprise the PCK that teachers drew upon and developed, which can be useful for themselves, for other teachers and teacher candidates, as well as for professional development leaders. Teachers’ PCK fosters students’ higher order learning of science content and processes, beyond more specific skills about the use of instruments, as necessary as those skills are. For example, readers of this study have gained ideas about how to engage students in using technology to conduct authentic scientific inquiry rather than remaining stuck at the point where students are simply learning about technology itself and how to operate the controls. Admittedly, there are indeed a number of useful descriptions in Chapter Four that one could reasonably characterize as so-called tips and tricks for how to usefully structure activities and instructions for students to ensure that students are viewing samples using the correct lens and saving and efficiently transferring images from one platform to another. However, the more powerful take-away in my mind is the underlying rationales teachers provided for why they chose specific instructional strategies and how their thinking changed about how to improve students’ learning experiences.

For instance, a number of teachers noticed that some students found it difficult to learn background knowledge about natural phenomenon while at the same time learning the nanoscale concept and learning to use two microscopes they had never before manipulated. Teachers described how their PCK changed as they developed new rationales that informed their ideas for scaffolding learning experiences working with and without technology so that students were adequately prepared to successfully negotiate the tasks required in each successive lesson.
Furthermore, the descriptions of teachers’ thinking provided here are not entirely linear in nature moving from emerging to proficient instructional choices, but rather this dissertation provides descriptions of the context of the decisions and the rationales that teachers applied to discern what they thought would be effective, developmentally appropriate instructional strategies to teach specific topics in science, during a particular time in the academic year working with particular groups of students. By providing this rich and thick description of the context in which the decisions were made, educators can gain a better understanding about the factors that contributed to the development of the Project NANO teachers’ rationales. Consequently, educators are also better supported to consider factors that exist in their own teaching contexts that ought to be considered when developing their own rationales to inform their instructional choices.

**#2 The Power of metastrategic thinking and PCK for research and teacher learning.** If the reader takes nothing else from this research, the most important idea that I want to foreground is that the combination of the constructs of metastrategic thinking and PCK used in this study focused teachers’ thinking and discussions beyond the point of choosing a series of favorite activities to create a unit plan. Indeed, the combination fostered teachers’ higher order thinking in the context of this design-based research and professional development project. Thus, this study demonstrates a design-based research approach that added significant value to the participants’ experience of professional development focused on the negotiation of novel science content and technology in the secondary curriculum. I further argue that the benefit of this approach is not limited to
professional development involving nanoscale content and technology or even PD involving any technology.

By using the metastrategic thinking and PCK frameworks together, participants in this study developed a sense of ease over the course of the year with thinking deeply and talking about their rationales that informed their instructional choices throughout the Project NANO unit. The call-out reflections protocol helped teachers to maintain a healthy skepticism about their choices and reflect on how to improve student learning by either fine-tuning or radically re-conceiving the way they had structured the learning opportunities. Because the interview questions were drawn directly from teachers’ call-outs and each successive interview and classroom observation, teachers’ reflections were focused on responding to their own authentic reflections rather than what may have appeared to be external and possibly random prompts that did not address the ideas they were currently negotiating in their own minds. Teachers not only developed language used to describe their thinking and the development and changes of their rationales, but also their own earlier comments facilitated their thinking deeply about the choices they said they made and why they made the choices they made. The teachers’ familiarity with the language they developed to describe their own thought processes means that the methodology is one that this set of teachers are now empowered to apply to consider other problems of practice beyond the Project NANO unit of instruction.

Due to the nature of Project NANO and this dissertation research, each teacher was asked to operate as an adaptive expert (Bransford, 2001) willing to enter into a state of disequilibrium to figure out how to integrate new concepts and technologies into the
curriculum. Because the Project NANO team believed that learning to know and think like a teacher means developing the knowledge of teaching used and developed within practice (Feiman-Nemser, 2008), the program did not simply introduce teachers to the technology. Instead, teachers were explicitly asked and supported to integrate nanoscale science concepts and technology first into their own body of knowledge and, second, into the curriculum using their metastrategic thinking and PCK. The program explicitly structured experiences to support teachers to function as adaptive experts (Bransford, 2001) and to not treat nanoscale concepts and technology as an extra or disconnected add-on to the curriculum, but rather as an integrated part of their science course. We did this by explicitly working with teachers to draw upon and develop their PCK in extremely practical ways to assist them to tolerate the ambiguity as they let go of previously held assumptions about the nature of science as they gained new skills and knowledge. We worked to help teachers to integrate this new knowledge within existing domains of knowledge and provided tools to support and capture their reflective process in such a way to serve as continuing resources to themselves and those supporting them. Thus, this work and similar studies make important contributions to not only nanoscale education research but also to the adaptive expertise research that fits within the learning progressions framework of research and builds off of the earlier, but in some ways slightly different, learning-to-learn body of literature.

To my way of thinking, inspiring people to reflect upon implications of research on their own habits of mind to inform their practice is a central purpose of conducting educational case study research. The methodologies employed in this study demonstrate
an approach that fulfills this fundamental goal of case study research and is, therefore, an example of a very promising approach to improving teacher professional development and science education in the United States.

**Implications and Recommendations**

Here, I discuss implications of this research to inform teacher professional development, educational policy and research and offer recommendations based upon what I have learned from the experience of conducting this research. I begin with a description of implications of this research for teacher professional development along with a set of recommendations.

**Teachers’ professional development.** First, I submit and recommend that PCK be consciously employed by professional development leaders as a useful heuristic to foster and elicit teachers' thinking, as well as the communication of their thinking. The notion that PCK can be used as a heuristic to inform PD design has been widely accepted among the science education community for some time; however to date, teachers’ learning progressions have yet to be adequately studied (Schneider and Plasman, 2011). This dearth of knowledge about teachers’ learning progressions may contribute to common problems in educational reform. For example, although many science teacher professional development programs utilize a social constructivist approach, given that there is little known about teachers learning progressions, it is difficult for PD providers to anticipate teachers’ prior knowledge or PCK to calibrate supports for teachers that properly scaffold learning experiences in PD situations as teachers learn new content and skills.
Thus, I also contend and recommend that the design-based research strategy of Resource Folios be regularly integrated in professional development as a powerful, promising, and useful approach to calibrate support for teachers. The Resource Folios approach was originally created by the Loughran research group in recognition of the potential to improve teacher education and professional development by providing vehicles to support teachers’ learning and their abilities to communicate their PCK and, therefore, to inform collaborative efforts to improve teaching practices. However, even with the aid of such vehicles used to support teachers' reflective practices, in my experience, secondary teachers are often hesitant to publically admit that there are topics in science they are less familiar with or are uncomfortable teaching. Therefore, it is often difficult to inspire teachers to surface tacit knowledge, describe or even identify weaknesses in their body of PCK. This lack of comfort often makes it difficult for teachers to talk about what they need to learn in order to improve their practice. But in this case, nanoscale science and technology lay well beyond most teachers’ experiences, a situation of which every teacher involved in Project NANO was well aware. In this circumstance, regardless of years of experience in science, teaching or both, every participant recognized him or herself as an informed novice (Schneider and Plasman, 2011), working collaboratively to integrate concepts and technology that were new to all of the participants in the program. This awareness served to break down barriers of communication as teachers were critically aware of the importance and purposes of collaboration as they engaged in the complex task of learning new PCK and unit planning simultaneously.
Further, the Resource Folios research approach proved to be an effective tool for capturing teachers’ PCK as they worked with their colleagues, coaches, students and other forms of support to develop their own schema for how to integrate nanoscale science and technology into the curriculum by drawing on a wide variety of available resources. In particular, the use of the metastrategic thinking framework combined with the PCK construct have been shown in this study to be useful lenses for designing the elements of and interpreting Resource Folio data in such a way that coaches learned of teachers' needs in time to assist with problem solving and with effectively utilizing available resources as they actually implemented their units.

The implications of this contribution are many; however, at the forefront in my mind is that this study implies the need to use the plethora of practical, theoretically-based ideas for integrating nanoscale science and technology into the science curriculum using instructional strategies that inspire curiosity and wonder in learners that the study’s participants drew upon and developed. This was not a hypothetical study; it was very practical in nature and contributes to the dialogue within the science education community about how to support teachers to integrate nanoscale science and technology into the secondary curriculum in ways that could help avoid supporting the tips and tricks mentality that so often leads to activity-driven units rather than learning objective, student-driven units of instruction.

Rather, the results of this study imply the need to support teachers’ professional development and practice as adaptive experts. Bransford et al. (2005) described the concept of adaptive expertise as involving three major dimensions: processes that lead to
innovation or invention, processes that lead to increased efficiency through well practiced routines and “a meta-cognitive awareness of the distinctive roles and tradeoffs of the innovation and efficiency dimensions of expertise, and the active design and creative structuring of one’s learning environment in order to support their dual utilities” (Bransford et al., 2005, p. 54). In this study, Project NANO teachers and coaches exhibited thinking that involved all three of these dimensions, with all of the participants drawing upon complex schemas that allowed them to identify and address different problem types with organized procedures.

In addition to the overall desirability of teachers acting as adaptive experts in these three ways, the current state of curriculum also implies that teachers must function in these ways. To my knowledge there is currently only one nanoscale science secondary level curriculum available that explicitly provides guidance to teachers on how to draw upon nanoscale concepts to teach interdisciplinary topics in science, and that curriculum was only recently published (Madden, Hochellea, Glasson, Grady, Bank, Green, Norris, Hurst, & Eriksson, 2011). Therefore, to date, there is very little guidance available to support teachers to begin to develop new metastrategic thinking and PCK related to the integration of nanoscale science and technology into the curricula. This situation poses a particular problem in that nanoscale science is a discipline that lends itself very well to teaching using a multi-disciplinary scientific approach, however most current science curriculum is not designed using a multi-disciplinary scientific approach to knowing and most teachers are trained in only one or, at most, two disciplines of science such as biology and chemistry (Stevens et al., 2009). These conditions imply that teachers must
function as adaptive experts on all three of the dimensions described by Bransford et al. (2005) to learn to effectively draw upon the disparate resources currently available to integrate nanoscale science content and technology into existing curricular materials, including materials from disciplines that are outside of their usual domain of science that they teach.

Admittedly, even after nanoscale science curricula are fully developed and tested, it will continue to be up to teachers to adapt materials and instructional strategies to meet the specific needs of the learners they work with. To be able to do this effectively, teachers need support to learn new knowledge, skills and language used to describe scientific concepts and processes in various disciplines of science.

The descriptions of teachers’ metastrategic thinking and PCK contain herein have the potential to contribute to the implementation of the Next Generation Science Standards because the ideas shared here could inform professional development leaders and teachers’ abilities to anticipate student thinking and adapt instruction to meet the needs of learners in a reflexive manner using strategies such as those resulting from this study.

**Policy.** Here, I provide recommendations for state and federal level educational policy followed by district and school level policy recommendations. First, at the state and federal level I recommend that policies be created to support the establishment of state-level networks focused on the career-long teacher professional development of K-12 educators. Currently, many school districts in the U.S. focus primarily on providing PD support for early-career teachers and provide less professional development for mid-
career and veteran teachers. (Darling-Hammond, 1996). This situation ignores the reality that professionals benefit from well-designed supports to continuously improve practice throughout an entire career. In other words, a lack of professional development across all stages of the teaching career also implies a belief that once an educator “learns to teach,” what follows is only use of that knowledge, even as conditions change. However, given the new demands posed by the Common Core and Next Generation Science Standards (Achieve, 2013), the need to leverage resources in new ways is becoming increasingly important. Experienced teachers possess PCK that may be useful to others; however, adult learning theory suggests that excellent secondary level teachers are not necessarily automatically excellent teacher professional development providers. Therefore, I recommend the creation of policies that support a research-based approach to preparing veteran teachers to serve as coaches to facilitate the development of their peers’ metastrategic thinking and PCK to improve instruction. Furthermore, I also recommend that policies be created to support networking across organizations such as universities, educational non-profits and cross-district partnerships to provide opportunities that leverage multiple resources to support preparing experienced educators to participate in the development of innovative PDs that are consistent with district and state level school improvement initiatives. Optimally, funding researchers to support design-based studies that serve to examine and refine these innovative PDs will ensure that resources are expended in an effective manner and that teachers and students receive the best possible support from these experiences.
A second recommendation is that states collaborate with the federal government to support the continuation of programs such as the Math and Science Partnership Program, Discovery Research K-12 and other grant funded initiatives to support research-based teacher professional development. Specifically, I recommend that these competitively awarded grants support the purchase and maintenance of research grade instruments so that students have the opportunity to engage in authentic inquiry experiences in preparation to work in STEM fields including those related to nanoscale technology. Doing so will prepare U.S. students to fill the more than 50,000 nanoscale science related jobs estimated to be created in the next decade in the U.S. (Roco, 2010).

Teachers in this study reported that due to large classes and limitation of time, it was difficult to ensure that every student had the opportunity to adequately explore what could be learned using the microscopes. Thus, students’ opportunities to fully engage in an open-ended inquiry process were cut short. Teachers reported that they became increasingly directive rather than facilitative as they ran out of time to have the SEM and Leica in their classroom. Although reducing class sizes by improving and stabilizing school funding mechanisms is ultimately one necessary policy change that would do much to relieve this problem, simply putting additional technology into circulation could expand the amount of time each student has to conduct authentic inquiries and relieve a significant amount of stress on the part of teachers and students.

Next I submit two district and school level policy recommendations for consideration. First, I recommend that school district-level policies be adopted and funded to support design-based teacher professional development partnerships involving
university disciplinary faculty, veteran science teachers working to provide support to teachers and students to ensure continuous improvement of programs working to support educational reform by implementing new content standards in schools. Here in Oregon a common saying among the members of the ranching community is that weighing cows doesn’t fatten them up; feeding cows fattens the cows. Similarly, writing new standards and state level assessments does not prepare teachers to implement new standards. Providing well-conceived practical support over extended periods of time prepares teachers to implement new standards.

Project NANO provides an example of a program wherein two veteran teachers worked with a university level geologist and science education expert to intentionally prepare the veteran teachers to mentor other teachers. To make this possible, a local university and school district each agreed to support .25 FTE of one of these teachers’ classroom release time so that he could coordinate program activities, receive technical training using the microscopes and provide coaching to teachers during the academic year. The role that the TOSA served as an organizational bridge significantly increased the level of appropriate support provided to participants in the program. Importantly, this support aligned with the current conditions existing in schools with which we worked rather than competing with multiple initiatives as is so often the case and cause for failure of well-intentioned efforts to shift teaching practices (Darling-Hammond, 1996). Thus, district level policies that support not only the funding for release time but policies that support collaboration across traditional organizational boundaries are necessary to better
leverage resources across institutions to support career-long professional development for educators.

A second important district level policy recommendation is that of partnering with outside organizations such as non-profits and businesses to recruit trained scientists as volunteers so that well-prepared adults could facilitate students using sophisticated technology as planned by their secondary teachers. I recommend that teachers and university disciplinary faculty partner to design volunteer training programs to prepare scientists to facilitate rather than direct inquiry-based experiences working with research grade technology and leading edge scientific concepts. Such training programs would expose students to authentic scientific experiences while allowing the teachers to circulate among students providing guidance and support as necessary.

Finally, I recommend that districts and schools reconsider the adoption of scripted science curriculum. I believe that attempts to “teacher proof” instruction fail to recognize the crucial role of the teachers as professionals who draw upon their adaptive expertise (Bransford et al., 2005) to facilitate learning experiences that are sensitive to the needs of students – that is, individuals and specific groups of students – as well as changing educational needs and circumstances. By redirecting district and school level resources away from scripted curricula training toward professional development opportunities that build upon teachers’ PCK to effectively meet the specific intellectual and emotional needs of students, I argue that students will receive better instruction. Such instruction serves to not only improve student learning outcomes in the academic sense but also
instills in students a love of science as a means to explore and interpret the world they live in.

**Future research**

The most compelling idea for future research for me as a researcher is the possibility of continuing to examine the thinking of this set of 23 secondary level teachers as they adapt their thinking and improve upon their units of instruction over the next three years. Because I am also the internal evaluator for Project NANO, I was able to continue to collect and examine data beyond the data collection period for the dissertation. However, analysis of the data collected between March and June of 2013 for the program evaluation is different than the analysis applied to the dissertation data. I would like to apply the methods used in this dissertation study to complete an analysis of data for the entire group of 23 participants and if possible, continue to study this group of teachers with a goal of describing the development of their PCK and metastrategic thinking over time.

Another potential area of future research is an examination of how to most effectively integrate pre-service with in-service teachers in the same teacher professional development programs. Although the topic of how to effectively integrate in-service and pre-service teachers into one PD was not the subject of this dissertation research, Project NANO operates on the idea that scientifically trained pre-service teachers contribute knowledge gained through field and lab experiences to groups of in-service teachers who bring a wide range of PCK to the inquiry and unit. Involving less than half as many pre-service teachers as experienced in-service teachers appeared to be more successful in
terms of establishing productive, collaborative relationships, as well as producing units of
instruction that scored well using the scoring guide and the EQUIP tools. Two interesting
questions for future research would be: what are effective strategies for integrating pre-
service and in-service teachers together in a professional development program and is
there an optimal ratio of student-teacher to in-service teacher participants in a science
teacher professional development program?

The Project NANO team also noticed that those pre-service teachers who co-
planned their units with the teacher who became their so-called cooperating teachers in
their student teaching classrooms reported high levels of success both in the planning and
implementation phases of the experience. Future research could be focused on examining
and describing the elements of such working relationships that contribute to pre-service
teacher candidates’ success both in terms of the student teacher’s experience and their
secondary level students’ learning outcomes. It would also be interesting to capture
student teachers’ later ideas about how such a partnership experience impacted their
overall student teaching experience and impacts on thinking about teaching during the
induction period.

Further research that I would like to participate in and highly recommend that
other scholars consider relates to the investigation of teachers’ learning progressions in
science education, particularly research related to how teachers negotiate the inclusion of
novel science and technology into the curriculum. I learned that some of the methods I
chose to use in the study such as the pre and post survey and a hierarchical rubric
confined the examination of teachers’ metastrategic thinking and PCK to fairly linear
descriptions. However, as is the case with several researchers working with the learning progressions construct (e.g. Wilson, Floden, & Ferrini-Mundy (2001), and Shavelson, 2009), people don’t necessarily think or learn in a linear manner. Therefore, I’m interested in exploring research methodologies that build upon the strengths of the Resource Folios approach to develop a more systems-based approach to describe cross-cutting concepts of both the science and technology and teachers’ metastrategic thinking and PCK about how to teach specific topics to students at particular developmental levels.

As Wilson, Floden, and Ferrini-Mundy (2001), Berliner (1994) and more recently Schneider and Plasman (2011) have pointed out, even though the learning progressions construct for student learning has rapidly gained wide-spread attention, there are currently few studies examining how teachers’ knowledge progresses with instruction. Studies that examine elements such as how teachers progressively learn new content and how they think about testing and evaluating various instructional strategies to improve student learning in response to teacher professional development would fill critical gaps in understanding how to effectively design teacher professional development experiences.

Reflections

This dissertation research represents the culmination of six years of thoughtful planning, testing, examination and reflection. The study began with a conversation about how to leverage PCK from university level disciplinary faculty members and veteran secondary level science teachers to provide teacher professional development involving leading edge concepts and scientific tools. Project NANO developed based on a theory of
practice centered on social constructivism and situated learning. This lens was applied to every aspect of the program to understand the development of the disciplinary geologist who learned about the culture of teaching at the secondary level and the two veteran teachers leaders who spent three years co-teaching the summer workshops with the university geologist, refining their own nanoscale units of instruction in their own high school chemistry courses and refining their approach to teaching and providing follow-up coaching support to cohorts of teachers involved in the program.

This theoretical lens also applies to me, as well as to my role within the program. I started out as a co-investigator designing the program and securing funding to purchase the SEMs and Leica and cover the attendant costs of the program. I learned how to switch from the role of co-program developer working to support program coordination to that of a design-based researcher and internal evaluator. I chose to approach this research by basically laying down a descriptive baseline for the program. Such experience provided me with the opportunity to step back from the work that is my life passion and apply a more dispassionate eye to examine teacher thinking within the context of the structure I co-developed.

I have had the honor to work with a community of practice partnership between a public university in the Pacific Northwest of the U.S. and local school districts that have developed a repertoire of elements to form the essential framework for each science teacher professional development program offered through the partnership. These elements are depicted in Figure 15.
Figure 15. Key elements of the Project NANO program design.

Although some of the instructional strategies used to frame content and skills differ among the various teacher professional development programs I have been involved with through these partnerships, these elements are essential to each, including Project NANO. Although the dissertation study is not an evaluation of the impacts of the each of these elements on teacher thinking, this research has served as an opportunity to closely examine how teachers think within the context of this particular teacher professional development program that includes this particular set of research-based elements.
Many interesting thematic patterns of teachers’ thinking arose throughout this study. One of the most prevalent and, to me, inspirational themes was voiced by a middle-level teacher following the implementation of her unit of instruction:

A theme that we keep coming back to is that when we think about the world around us, we need to keep in mind that there are different perspectives (scales) that can be considered; if we only look at and think about the world from the perspective of what we can see with our eyes we will miss important connections and information.

This research described teachers thinking on the leading edge of science and science teaching, teachers who willingly entered into a situation that demanded that they consider problems of practice from new perspectives. Thanks to the 2012 Project NANO teachers’ willingness to step to that edge and describe how, as social constructivists within a situated learning environment, they negotiated the affordances and challenges of the situation, this study contributes to a body of knowledge critical to supporting the implementation of the Next Generation Science Standards (Achieve, 2013) and the Common Core. Furthermore, this research contributes to a body of knowledge that has the possibility of ensuring that the next generation of scientific thinkers is empowered to engage in the nanoworld as citizens prepared to think and learn and possibly, contribute to solutions for problems that we don’t even know we have yet.

**Conclusion**

An important lesson from this research regards professional development that enhances teachers’ own higher order thinking. Just as well thought-out instructional strategies used in secondary classrooms have the potential to facilitate students to use and develop higher order thinking skills, well-chosen and designed instructional strategies
employed in teacher professional development contexts have the power to stimulate teachers' higher order thinking used to develop and test rationales for how to frame learning and teaching opportunities. Although many of the examples of teachers' metastrategic thinking and PCK described in this dissertation research are fairly specific to how teachers approached problem solving as negotiated the inclusion of nanoscale science and technology into the curriculum, the methods used in this study also served to elicit numerous examples of teachers' rationales for their choices of instructional strategies that are more general in nature. Thus, this study contributes not only to the small but growing body of literature that examines teachers' PCK, learning progressions and adaptive expertise related to nanoscale science and technology, but also it contributes to the broader literature related to scientific inquiry.

This dissertation research including the compendium of Resource Folios found in the appendices may be of use to teacher professional development providers, pre-service teachers, educators teaching outside of their traditional discipline and anyone negotiating the inclusion of novel science and technology into the modern curriculum. Loughran et al. (2006) made the point that the Resource Folios approach is founded on the idea of switching from the traditional question of how do you teach this topic? to what is it that you know about this topic and student thinking that informs your rationale for making specific instructional choices to meet the developmental needs of particular group of students? Shifting to the latter question stimulates teachers to employ their own higher order thinking skills to respond. As a result of reframing the question in this way by using the Resource Folios approach, this study provides a description of the PCK and
metastrategic thinking employed by teachers in Project NANO. The study’s results may support educators to be better informed so that they are enabled to function as listeners sensitive to cues from students and act as co-learners within a community of practice that includes everyone in the room.

It is my hope that teachers reading this work will be better prepared to understand how to frame learning experiences for students and respond to evidence of student thinking in a flexible manner. I hope that educators will draw upon the lessons learned from the descriptions of these teachers’ PCK and metastrategic thinking and as a result become more expert designing rigorous learning experiences, anticipating student thinking in the pre-planning stages and throughout the implementation of the unit and responding to students specific needs based on knowledge of the content, curriculum and student thinking.

Given the pressures that teachers and students are experiencing in the modern science classroom to rapidly integrate novel science and technology into the curriculum while at the same time improving learning and teaching of topics historically taught at the secondary level, this study provides support to increase the potential for students and teachers to function as co-learners. Given what we know about how students learn science, this study provides an important resource to support the implementation of the Next Generation Science Standards.

Perhaps even more importantly, this work has the potential to support educators to design learning opportunities that support students to develop content knowledge and habits of mind that will assist them in pursuing questions they have about the natural and
built world and, in general, live in a state of curiosity and wonder with tools they can use to pursue their interests as member of society. Thus, this examination of teachers’ PCK and metastrategic thinking used to consider how to teach about the nanoscale can have important impacts on the world of science education and beyond.

**EPILOGUE**

From this experience, I have gained important practical insights related to educational leadership. As a long-time social constructivist, I understand that no two learners begin or end in the same place as the result of a learning experience. Everyone brings strengths and limitations that influence what a teacher is able to effectively integrate into his or her body of knowledge. An important goal of teacher professional development is to provide experiences that leverage the knowledge and skills each participant brings to the situation to build new capacities for teaching and learning. A further goal is to provide useful, practical support such that new content and technology is eased into the curriculum in a thoughtful, reflective manner. However, calibrating instruction to suit a variety of instructional needs remains the greatest challenge of my career. Just as expert secondary teachers learn to listen in the hermeneutic sense as co-learners, this experience has refined my expertise as a listener - which is a good thing, because it is clear that collectively teachers have quite a few good ideas to offer for how to negotiate complex yet common problems of practice.

One of the most important set of skills a leader must possess is the ability see problems from multiple perspectives and then frame questions that seek to reveal fundamental knowledge to inform systems level improvement. As a result of this doctoral
experience, I believe that my ability to frame questions in powerful ways has greatly improved simply because my base of knowledge is now considerably more rich and complex than it was prior to entering this Educational Leadership doctoral program. Understanding more about how teachers form rationales for choosing how to structure units and how to select pedagogical strategies drawing on their PCK is critical to my development as a professional developer, researcher and teacher.

Although tools such as the metastrategic thinking and PCK frameworks are helpful in the effort to elicit and describe thinking, an observer must take care to avoid potential bias. The doctoral experience has guided the development of my ability to interpret teachers’ PCK using research tools that ensure a less biased approach to listening and observing. The use of Resource Folios provided an established, elegantly simple structure that allows teachers to express and respond to their own current and new thinking about questions fundamental to teaching and learning. The use of these tools provided teachers with sufficient supports to share ideas which foregrounded the teachers’ thinking in this study rather than the instruments or my own thoughts. I plan to continue to work towards further refinement of research designs that provide for stories to be told authentically and without bias – stories that illuminate thinking for self-reflection and that will assist others in developing their own approaches for teaching diverse learners in a constantly changing environment.

Ideas both lofty and small influence who I have become as an educational leader over the past four years I have spent as a doctoral student. I will carry this work forward in the spirit of an adaptive expert willing to play the role of an intelligent novice stepping
out on the leading edge of change. The time has come to look at the world in new ways
from a variety of perspectives. This project, one that allows a very deep look into the
nature of matter, serves as an excellent metaphor for my own self-concept of how I
operate in the world as an educational leader. I am a leader who uses the tools afforded to
us by modern science and our own minds to look deeply into the underlying rationales
that motivates choices and action. May this experience of reading about teacher thinking
in the context of Project NANO serve to support your efforts to build upon the leading
edge of change as well.
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APPENDIX A

CASE-BY-CASE STUDY OF FOUR TEACHER PARTICIPANTS: PAUL
**Introduction**

The following presents four cases in the form of Resource Folios. These Resource Folios are comprised of Content Representation (CoRe) tables and Professional and Pedagogical Experience Repertoires (PaP-eRs). All of the following that is not explicitly labeled as a CoRe are PaP-eRs. The purpose of these case-by-case examinations is to present a profile of four teachers’ metastrategic thinking and PCK as they negotiated the inclusion of nanoscale science and nano technology into the secondary level curriculum. The PaP-eRs are comprised of each teacher’s unit of instruction and scoring guide scores, pre and post survey data, classroom observation data, and CoRe call-out reflections coded interviews. Each case will highlight explicit observations developed from the data that draw connections between the respective teacher’s background experiences in science and science teaching, their level of PCK relative to nanoscale concepts and technology, their metastrategic rationales for the instructional strategies they chose to employ in their Project NANO unit and their reflections that inform changes in their PCK and the unit plan.

The criteria of selection used to choose the four cases are: two veteran and two novice teachers, each from different schools, four unique units of instruction, and teachers who completed the implementation and reflection cycle by February of 2013. The four teachers chosen for the cases include a novice high school chemistry teacher, a novice high school chemistry and biology teacher, a veteran high school engineering design teacher and a veteran middle school integrated sciences teacher. Each of the teachers has been assigned a pseudonym to protect the confidentiality of the participants.
Paul

Paul (pseudonym) teaches sophomore chemistry and IB chemistry in a comprehensive suburban, public school. He taught the Project NANO unit in his two introductory chemistry classes comprised of students that are grouped by ability levels according to their performance on a math placement test students took at the beginning of the 2012-2013 academic year. One of the two classes is primarily comprised of high-ability level students and the other class is primarily comprised of low ability students, 75% of which are on Individualized Educational Plans (IEP) and have a variety of special needs. Both classes include English Language Learners at a low level of language acquisition and both classes include forty-three students in a classroom designed to optimally hold thirty to thirty-five students according to the teacher and building Principal.

Paul is currently in his second year of teaching at the high school level and has three years of experiencing teaching introductory chemistry classes as a teaching assistant at the college level prior to becoming a high school teacher. Paul is a National Science Foundation Robert Noyce Teacher Scholars Program fellow, which means that he graduated from a highly rigorous graduate level program that involved earning both a Masters in Science Teaching degree and completing the requirements for secondary teaching licensure with a chemistry endorsement. He has taken over ten college-level science courses, six of which were at the graduate level. Paul reports in the pre survey that he took at the beginning of the summer workshop that he teaches science as inquiry most of the time.
In the interest of full-disclosure, I have known Paul for five years in a professional capacity. I served as the program coordinator for the Noyce program during the time that Paul was enrolled as a Noyce Scholar and I served as the instructor for two of his Masters level science education courses. I also worked with Paul and his thesis research advisor to design his Master’s thesis research project and I served as a liaison between the three departments that Paul was involved with throughout his master’s program. One of the courses that Paul took from me was entitled *Teaching Science with Technology*, thus I am aware of some of the pedagogical content knowledge instruction that he received in this and other classes that potentially contribute to his thinking as a second year teacher. In addition, one of the two summer workshop instructors and Paul’s Project NANO coach mentored Paul during his student teaching experience and during his first year as a science teacher.

Paul reported in the summer workshop pre survey that prior to his involvement in Project NANO; he used digital and analogue scientific instruments both as a graduate research assistant in college and in his teaching practice, although he had no prior experience working with nanoscale science or technology previous to taking the Project NANO workshop. He also reported during the workshop that he did complete the pre-requisite homework assigned by the summer workshop instructors and that he entered the summer workshop with “a good idea” about the unifying concepts and big ideas he would include in the unit he developed during the workshop. He also collected a variety of samples to analyze with the SEM in the first day of the workshop to determine whether or not those samples would image properly. He found that all of the samples imaged well
and thus, he decided to fully develop the unit he had planned to create prior to entering the workshop.

**Paul’s Unit of Instruction**

Paul developed a two-week unit in collaboration with a pre-service teacher Sara (pseudonym), who holds a PhD. in chemistry and is in the process of changing careers from working with nanotechnology as a laboratory scientist at Intel Corporation to becoming a high school physics and chemistry teacher. Here is the unit of instruction developed by Paul and Sara:

**Learning Targets**

**State Targets**
H.1P.1 - Explain how atomic structure is related to the properties of elements and their position in the Periodic Table. Explain how the composition of the nucleus is related to isotopes and radioactivity.
H.1P.2 - Describe how different types and strengths of bonds affect the physical and chemical properties of compounds.

**District Learning Targets**

**Chemistry ALT 4 - I can classify matter based on physical and chemical properties**
AST 4.1 Scholar can convert between unit prefixes and scientific notation values
AST 4.2 Scholar can compare the characteristics of solids, liquids, and gases in terms of density, motion, and energy
AST 4.3 Scholar can differentiate between pure substances and mixtures, including differentiating among colloids, suspensions, and solutions based upon physical and chemical properties
AST 4.4 Scholar can identify a property of a substance as chemical or physical
# Lesson Plan Calendar

<table>
<thead>
<tr>
<th>Day</th>
<th>Learning Targets Addressed</th>
<th>Activities</th>
<th>Homework</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AST 4.1 Scholar can convert between unit prefixes and scientific notation values</td>
<td>30-Scales of the universe flash video and discussion</td>
<td>Read Chapter 3 pages 68-77 review/practice problems 3, 4, 7, 9, 11, 15, 18, 22, 23, 28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10- reflection on scales of universe discussion</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>20- Lecture on Sci notation and unit prefixes</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>30 – Sci not/prefixes lecture</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>AST 4.2 Scholar can compare the characteristics of solids, liquids, and gases in terms of density, motion, and energy</td>
<td>20- Lecture on phases of matter</td>
<td>Read Chapter 2 Page: 28-31</td>
</tr>
<tr>
<td></td>
<td>AST 4.3 Scholar can differentiate between pure substances and mixtures, including differentiating among colloids, suspensions, and solutions based upon physical and chemical properties</td>
<td>10- Phases of matter practice</td>
<td>Chapter 2 Problems: 2, 3, 6, 9, 17</td>
</tr>
<tr>
<td></td>
<td>AST 4.4 Scholar can identify a property of a substance as chemical or physical</td>
<td>20- Classifications of matter</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10- “What’s the matter” practice</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>20- Lecture on chemical and physical properties</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10- Chemical physical properties practice</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>AST 4.1, 4.2, 4.3, 4.4</td>
<td>80 - 4 SEM Lab cycles</td>
<td>Presentation prep</td>
</tr>
<tr>
<td>4</td>
<td>AST 4.1, 4.2, 4.3, 4.4</td>
<td>80 - 4 SEM Lab cycles</td>
<td>Presentation prep</td>
</tr>
<tr>
<td>5</td>
<td>AST 4.1, 4.2, 4.3, 4.4</td>
<td>40 - 2 SEM Lab Cycles extra SEM time/presentation prep</td>
<td>Presentation prep</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Unit test review</td>
</tr>
<tr>
<td>6</td>
<td>AST 4.1, 4.2, 4.3, 4.4</td>
<td>60- Lab group presentations</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>30- Unit test</td>
<td></td>
</tr>
</tbody>
</table>
Day 1 – Science and size

Scales of the universe flash and discussion
Walk through of flash video with teacher commentary and discussion. The teacher will have students record the sizes of several items from the flash video along with their notes for later use.

Anyone know what separates sciences?
Astronomy: Above 1000 km
Geology/biology/ecology/physiology: 1 mm – 1 Mm
microbiology/geochemistry/biochemistry: 1µm – 1 mm
Chemistry: 0.1 nm - 1 µm
Physics: “0” m – 0.1 nm

Scientific notation and unit prefixes Lecture
Lecture notes:
What do exponents do to numbers? What do they do to 10’s?

\[
\begin{align*}
10^9 &= 0.000000001 \text{ nano n} \\
10^6 &= 0.000001 \text{ micro µ} \\
10^3 &= 10/10/10/10/10/10 = 0.001 \text{ milli m} \\
10^2 &= 10/10/10/10/10 = 0.01 \text{ centi c} \\
10^1 &= 10/10/10 = 0.1 \\
10^0 &= 10/10 = 1 \\
10^1 &= 10 \\
10^2 &= 10 x 10 = 100 \text{ deci d} \\
10^3 &= 10 x 10 x 10 = 1000 \text{ kilo k} \\
10^6 &= 1,000,000 \text{ Mega M} \\
10^9 &= 1,000,000,000 \text{ Giga G}
\end{align*}
\]

Scientific Notation: Used to express extremely large or small numbers in a compact way.

4590000000 = 4.59 x 100000000 = 4.59 x 10^8
0.00000224 = 2.24 x 0.00001 = 2.24 x 10^{-5}

Alternatively can use prefixes… 0.459 Giga or 22.4 µ

To do math with these numbers enter them in calculator with parenthesis around whole number!

Scientific notation and unit prefixes practice
Students will be prompted to make several conversions using the size values recorded during the scales of the universe flash video; for example: convert the size of the milky way galaxy into Gigameter, now write this number in scientific notation; or, convert the size of a water molecule into scientific notation, now convert it into picometers.
Day 2 - Matter

Phases of Matter Lecture Notes

Phase: Any region of a material that has its own set of properties
Bose-Einstein Condensate: Near absolute zero liquid where atoms become waves.
Waves overlap to become one unified piece of matter, may be used for reducing large lasers into tiny space, also may be used to study “vortices” phenomena that occurs in the waves that mimic black holes.
Solid: Can hold its shape and has fixed volume
Liquid: Takes shape of container and has fixed volume
Gas: Takes shape and volume of container
Plasma: Completely ionized gas atoms

What is the most common phase of matter in the universe? ☺ Turns out plasma makes up more than 99% of known matter. Think about how massive stars are…

<table>
<thead>
<tr>
<th>Solid</th>
<th>liquids</th>
<th>gases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>High</td>
<td>High (sometimes more than solid!)</td>
</tr>
<tr>
<td>Motion</td>
<td>Low</td>
<td>Middle</td>
</tr>
<tr>
<td>Energy</td>
<td>Low</td>
<td>Middle</td>
</tr>
</tbody>
</table>

Bose-Einstein condensate
Classifications of Matter Lecture Notes

Pure Substance: (very general) Any pure chemical. (any element or compound)
  atoms: the smallest particle of an element that retains the chemical identity of that element.

Element: Cannot be changed to another substance by chemical means.
  (each element has a unique number of protons)
  compounds/molecules: two or more atoms chemically bonded together

Mixtures: Made up of multiple constituents.
  Consistency
    Heterogeneous mixture: An unevenly dispersed mixture
    Homogeneous: An evenly dispersed mixture
  Particle Size (“Particle:” (EXTREMELY general) A small spherical bit of mass)
    Suspension: Largest particles above 1000 nm or 1 µm in diameter
    Colloid: Small, molecular-sized, not atomic sized particles from 1 nm – 1000 nm in diameter or 0.001 µm – 1 µm
    Solution: Extremely small atom-sized particles under 1 nm or
Lecture notes for chemical and physical properties

Intensive Properties: Do not depend on the amount of a substance present (color, density, viscosity, malleability, luster…)

Extensive Properties: DO depend on the amount of a substance (mass, volume, energy, pressure…)

Physical property: observable without chemical reaction
Examples of physical properties are: color, smell, freezing point, boiling point, melting point, infra-red spectrum, attraction (paramagnetic) or repulsion (diamagnetic) to magnets, opacity, viscosity and density. There are many more examples. Note that measuring each of these properties will not alter the basic nature of the substance.

Physical properties to look for in SEM lab: color, particle size, shape/structure, CHARGING/conductivity, consistency, phase at room temp, and texture.

Chemical property: Only observable as a result of chemical reaction
Examples of chemical properties are: heat of combustion, reactivity with water, PH, and electromotive force. Measuring chemical properties almost always results in changing the chemical into a different/new chemical.

Day 3, 4, and 5 – SEM Lab
Station 1: element, compound, molecule, homogeneous mixture, or homogeneous mixture?
Objectives:
- Analyze the samples visually
- Analyze the samples under the light microscope
- Analyze the SEM Pictures for each sample
- Select 5 samples as examples of each of the 5 classifications: element, compound, molecule, homogeneous, or heterogeneous mixture
Directions:
1.) Write in observations on this chart for each of your 5 samples. Be as detailed as possible!
2.) Once complete, cross-reference with the chart of identifiable physical properties to determine classification of matter for samples.

Chart of identifiable physical properties of different classifications of matter:

<table>
<thead>
<tr>
<th>Matter Type</th>
<th>Color</th>
<th>Luster</th>
<th>Shape/structure</th>
<th>Particle size in mixtures</th>
<th>Conductivity (high conductivity = low charging)</th>
<th>Phase at room temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elemental</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metals</td>
<td>Bronze, silver, gold (can be different ...)</td>
<td>Very shiny</td>
<td>Cubic crystals or spherical drop shapes</td>
<td>Nano Below 1 nm</td>
<td>Highly conductive</td>
<td>Solid</td>
</tr>
<tr>
<td>Nonmetals</td>
<td>Various colors</td>
<td>Little/no luster</td>
<td>Clumps, flakes, powder, oil, goo</td>
<td>1 nm–1000 nm</td>
<td>Little/none</td>
<td>Solid, liquid, gas</td>
</tr>
<tr>
<td>Compounds/ Molecules</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Compounds</td>
<td>Clear, white, various colors</td>
<td>Crystals usually reflective</td>
<td>Cubic crystals</td>
<td>Nano Below 1 nm</td>
<td>Inconsistent “speckled” charging</td>
<td>Solid</td>
</tr>
<tr>
<td>Molecules</td>
<td>Various colors</td>
<td>Little/no luster</td>
<td>Clumpy, colloids, flakes, powder, oil, spheres, goo</td>
<td>1 nm–1000 nm</td>
<td>Little/none</td>
<td>Solids but usually liquid or gas</td>
</tr>
<tr>
<td>Mixtures</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consistency:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Homogeneous</td>
<td>Consistent color</td>
<td>Consistent luster</td>
<td>Consistent shape particle</td>
<td>Consistent conductivity</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Scientist data collection table:

**Directions:**
1.) Write in observations on this chart for each of your 5 samples. Be as detailed as possible!
2.) Once complete, cross-reference with the chart of identifiable physical properties to determine classification of matter for samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Color</th>
<th>Luster</th>
<th>Shape/structure</th>
<th>Particle size in mixtures</th>
<th>Conductivity (high conductivity = low charging)</th>
<th>Phase at room temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
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<td>2</td>
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<td>4</td>
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<td>5</td>
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</tr>
</tbody>
</table>

**Heterogeneous**

- Various sizes
- Both luster particles and none luster
- Various clearly different shapes and structures
- Various sizes
- Both conductive and non-conductive particles
- Solid, liquid, or gas (sometimes 1 or more phases)
Station 2: suspensions, colloids, solutions

Objectives:
- Analyze the solid and “dissolved” samples visually
- Analyze the samples under the light microscope
- Analyze the SEM Pictures for each sample
- Determine which samples are suspensions, colloids, and which are solutions

Directions:
1.) Observe the samples visually as a solid and when dissolved in water
2.) Observe samples under the light microscope, and via the provided SEM pictures for each sample
3.) Select three of the samples that are examples of a suspension, a colloid, and a solution

Chart of identifiable physical properties of suspensions, colloids, and solutions:

<table>
<thead>
<tr>
<th>Matter Type</th>
<th>Shape/structure of particles when separated/dried</th>
<th>Turbidity (see through?)</th>
<th>Particle size when dissolved</th>
<th>Texture when dissolved in water</th>
<th>Phase when dissolved in water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suspension</td>
<td>Large shapes that can vary greatly in size and structure</td>
<td>Little or no visibility</td>
<td>Above 1000nm</td>
<td>Varies but basically “chunky” with visible solids</td>
<td>solid</td>
</tr>
<tr>
<td>Colloid</td>
<td>Small typically spherical particles</td>
<td>usually opaque or shaded in color</td>
<td>1nm-1000nm</td>
<td>Typically oily, smooth, waxy, filmy…</td>
<td>Very small solid clumps</td>
</tr>
<tr>
<td>Solution</td>
<td>Typically crystalline (cubic) or metallic structures</td>
<td>Clear when dissolved in water</td>
<td>Below 1nm</td>
<td>Typically seems just like water</td>
<td>Liquid</td>
</tr>
</tbody>
</table>

Scientist data collection table:
1.) Observe the samples visually as a solid and when dissolved in water
2.) Observe samples under the light microscope, and via the provided SEM pictures for each sample
3.) Select three of the samples that are examples of a suspension, a colloid, and a solution
### Sample
<table>
<thead>
<tr>
<th>Sample</th>
<th>Shape/structure of particles when separated/dried</th>
<th>Turbidity (see through?)</th>
<th>Particle size when dissolved</th>
<th>Texture when dissolved in water</th>
<th>Phase when dissolved in water</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<tr>
<td>2</td>
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<tr>
<td>3</td>
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</tbody>
</table>

### Station 3: How pure is “pure”?

#### Objectives:
- Analyze the samples visually, under the light microscope, and analyze the SEM Pictures for each sample.
- Determine which sample is “pure”.
- Write a half page reflection on the meaning of “purity”.

#### Microscope

- At this station you will need to collect 3-5 images of the coral sample as your data. You will need to record these images at different magnifications. For example, 8x, 16x, 25x, 35x. You will also need to use a photograph a standard at the same magnifications that you will use for your samples. All of these images will be used to help you determine the population density of a coral colony. **Procedure:** Follow protocols to capture, name and properly save images.

#### Some Microscope Terms
- **Depth of field** - vertical distance, from above to below the focal plane, that yields an acceptable image.
- **Field of view** - area of the specimen that can be seen through the microscope with a given objective lens.
- **Magnification** - product of the magnifying powers of the objective and eyepiece lenses.
- **Resolution** - the closest two objects can be before they’re no longer detected as separate objects (usually measured in nanometers, nm).

A light microscope, whether a simple student microscope or a complex research microscope, has the following basic systems:
- **Illumination** - shed light on the specimen.
  - **Lamp** - produces the light.
  - **Condenser** - lens system that aligns and focuses the light from the lamp onto the specimen.
  - **Diaphragms or pinhole apertures** - alter the amount of light, (for enhancing contrast in the image).
- **Lenses** - form the image.
  - **Objective lens** - gathers light from the specimen.
  - **Eyepiece** - transmits and magnifies the image from the objective lens to your eye.
  - **Nosepiece** - rotating mount that holds many objective lenses.
  - **Focus** - position the objective lens at the proper distance from the specimen.
  - **Coarse-focus knob** - used to bring the object into the focal plane of the objective lens.
  - **Fine-focus knob** - used to make fine adjustments to focus the image.

(Source: [http://science.howstuffworks.com/light-microscope5.htm](http://science.howstuffworks.com/light-microscope5.htm))
Station 4: How small is “small”?
Objectives:
- Solve a puzzle on sizes of objects in the universe
- Watch “Powers of Ten” video
- Write half page reflection on sizes of objects in the universe
Directions:
1.) Arrange the objects in the size puzzle from largest to smallest. Take time to work together and discuss the placement of each item.
2.) Check your arrangement against the key provided.
3.) Watch the “Power of Ten” video provided
4.) Write a half page reflection on sizes of things in the universe

Station 5: How massive is “mass”?
Wait… huh!?!
Objectives:
- Calculate the amount of air between 1000mL of marbles
- Calculate the amount of air between 50mL of pebble sand particles
- Calculate the amount of air between 50mL of fine sand particles
- Observe the mixing of alcohol and water
- Write a half page reflection on space between particles
Directions:

**WARNING! At no time should sand be put down the sink! Please dispose of the sands in the properly labeled wet sand containers. The sand will clog the sinks and take months to repair!**

*Note:* to wash wet sand that is “stuck” to the bottom of the graduated cylinder out into the wet sand buckets add water, cover the cylinder top with your hand, invert the cylinder, and shake vigorously to loosen the sand from the bottom of the cylinder, then dump in properly labeled container.

1.) Measure the volume of the dry marbles. This is the volume of the marbles + air

2.) Fill the graduated cylinder to about 400 mL and add the marbles. Marbles + water

3.) Subtract the volume of the water (~400 mL) from the volume of the marbles + water to get
just the volume of the marbles via displacement ________

4.) Divide the volume of the marbles in step 3 by the volume of the “marbles + air” in step 1 then multiply by 100 to get the percentage of volume of the marbles + air that comes from the marbles

\[
(\text{Volume of marbles}) / (\text{Volume of marbles + air}) \times 100 = \% \text{ volume that is marble} =
\]

5.) Subtract the “% volume that is marble” from 100% to get the % volume of air

Now repeat the same steps for the “pebble sand” and the “fine grain sand”

Pebble sand
1.) Sand + air (dry sand) ____________
Note: start step 2 with about 40 mL of water
then add sand to the water
2.) Sand + water (wet sand) ____________
3.) Sand (subtract water) ____________
4.) % volume of sand particles ____________
5.) % volume of air between sand __________

Fine grain sand
1.) Sand + air (dry sand) ____________
Note: start step 2 with about 40 mL of water
then add sand to the water
2.) Sand + water (wet sand) ____________
3.) Sand (subtract water) ____________
4.) % volume of sand particles ____________
5.) % volume of air between sand __________

Measure out EXACTLY 250 mL of ethyl alcohol and EXACTLY 250 mL of water. Mix the two together in a graduated cylinder. Measure the volume of the resulting solution.

Write a half page reflection on your observations on the air space percentages you calculated above. Also, what happened when you mixed the alcohol and water? Can you explain this phenomenon?

Station 6: How does an SEM work?
Objectives:
-Research the inner workings and scientific principals behind an SEM
-Create an explanation of how the SEM works

Directions:
1.) Read the available information on the principals of, construction, and design of an SEM
2.) Write a letter to a friend, make a comic strip, draw a detailed diagram, write a half page explanation, create a short story, or in some way write/draw an explanation in your own words of how an SEM works.

Turn this in as part of the Background section of your lab.
At this station you will need to show your understanding of how an SEM works by doing one of the following:

a. Creative tour of the scope (a journey through the microscope from an electrons perspective)

b. Labeled diagram of an SEM with explanation of workings

c. What would make this machine or images even better?

**Microscopes – Help Scientists Explore Hidden Worlds**

The microscope is an invaluable tool in today's research and education. It is used in a wide range of scientific fields, where major discoveries in biology, medicine and materials research are based on advances in microscopy. As the need to see the world at a smaller and smaller scale has grown scientist looked for ways to improve on the light microscope (see Fig. 1 below).
In 1938 Ernst Ruska developed the electron microscope and in 1981 Gerd Binnig and Heinrich Rohrer invented the scanning tunneling microscope that gives three-dimensional images of objects down to the atomic level. In 1986 all three men received the Nobel Prize in Physics.

The greater resolution and magnification of the electron microscope is because the wavelength of an electron: its de Broglie wavelength is much smaller than that of a photon of visible light. Conventional light microscopes use a series of glass lenses to bend light waves and create a magnified image. The electron microscope uses electrostatic and electromagnetic lenses in forming the image by controlling the electron beam to focus it on the surface of the specimen.

The SEM shows very detailed 3-dimensional images at much higher magnifications than is possible with a light microscope (because electrons travel at a smaller wavelength) but the images are in black and white because electrons don’t give off visible light (see Fig. 2 below).

To prevent electrons from colliding with air molecules all SEMs work under a vacuum. Initially samples are stuck down on a metal stub and have to be prepared carefully to withstand the vacuum inside the microscope. No wet, magnetic or live samples can go into an SEM.

Biological specimens are first dried in a special manner that prevents them from shriveling. Also because the SEM illuminates with electrons, they also have to be made to conduct electricity. SEM samples are often coated with a very thin layer of a metal (i.e. gold) by a machine called a sputter coater.

Once the specimen is prepared its ready to go into the SEM. The sample is placed inside the microscope’s vacuum column through an air-tight door. After the air is pumped out of the column, an electron gun [at the top] emits a beam of high energy electrons. This beam travels downward through a series of magnetic lenses designed to focus the electrons to a very fine spot. Near the bottom, a set of scanning coils moves the focused beam back and forth across the specimen, row by row, this is called rastering.

As the electron beam hits each spot on the sample, secondary electrons are knocked loose from its surface. A detector counts these electrons and sends the signals to an amplifier. The final image is built up from the number of electrons emitted from each spot on the sample.
How Does a SEM Work? (continued)

- The Scanning Electron Microscope is revealing new levels of detail and complexity in the amazing world of micro-organisms and miniature structures. Follow this link to a video that shows, generally, how an SEM works.

- **VIDEO LINK: SEM Video Link**
  http://www.youtube.com/watch?v=lrXM1ghANbg&eurl=http%3A%2F%2Fvideo%2Fg%2Eme%2F%2F videosearch%3Fq%3DElectron%2BMicroscope%26hl%3Den%26aq%3D0%26oq%3Delectron%2Bmic&feature=player_embedded

  - The good news is that the Phenom SEM that you will be using in class is a lot smaller and easier to use than the one shown in the above video but the Phenom work basically the same way as the SEM in the video. To see a brief preview of how to operate the Phenom go to the link below.

VIDEO LINK: **PHENOM Video Link**
http://www.youtube.com/watch?v=Rk7jGgMIPek&feature=related
Station 7: Presentation creation time

Objectives:
- Create a presentation on the identities of your 5 forms of matter

Directions
1.) Create a presentation that includes:
   __ A power-point, prezzi, google presentation, etc… visual
   __ Pictures from the SEM and light microscopes
   __ Evidence for the classification of your samples

2.) Create lecture notes. When presenting you are only allowed to read from your note cards/sheet and NOT directly from the power-point.

3.) Rehearse your presentation. Make sure you know who will say what, which visuals to reference, and what your main points are.

Station 8: SEM sample prep

Objectives:
- Prepare samples for imaging in the SEM
- Double and triple checking that samples meet safety parameters for the SEM

Directions:

1. Sample Prep
   1. All samples MUST be dry before mounting (use a desiccator if necessary).
   2. Once a sample is dry, carefully stick it to the metal stage of a mounting stub with carbon tape or carbon paste.
   3. To ensure that the sample is stuck down and clean, press it gently into the carbon tape, gently blow a little compressed air across it.
   4. Only samples less than 25 mm diameter x 30 mm thick should be loaded into the sample holder.
2.) Sketch and label your SEM samples using the blank circles below so that you know what is what later on!

![Blank circles for sketching SEM samples]

3.) Double-check via this checklist that your sample:
   
   ___ Is dry! And solid!   ___ You have sketched a key of samples above
   ___ Securely fastened to carbon tape   ___ You have fit 4 samples on each ring
   ___ Has been blown with condensed air   ___ Triple check…

4.) Start taking physical observations on your sample in the data collection table below with the naked eye. If time, try a light microscope to get a closer look…
Scientist SEM data collection table:

Directions:
1.) Write in observations on this chart for each of your 5 samples. Be as detailed as possible!
2.) Once complete, cross-reference with the chart of identifiable physical properties to determine classification of matter for samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Color</th>
<th>Luster</th>
<th>Shape/structure</th>
<th>Particle size in mixtures</th>
<th>Conductivity (high conductivity = low charging)</th>
<th>Phase at room temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Station 9: SEM analysis of samples
At this station you will need to collect 10-20 images of your sample you prepared. You will need to record these images at different magnifications. For example, 600x, 1000x, 2000x, 4000x. These images will be used to help you classify your 5 samples of matter.

Procedure: Follow your site protocols to capture, name and properly save images.
General guidelines for SEM specimen prep and use are below if you need a little help. Also refer to the Quick Reference Guide next to the SEM or ASK YOUR INSTRUCTOR for help.

System details
- Magnification range 20x – 20,000x
- Touch screen controlled
- Image options – JPEG, TIFF
- Sample load time <30 seconds

Station 10: Image “J” use on sample images
a. At this station you will need to go to the on-line Image J tutorial to learn how to ‘improve’ a picture. This software allows you to do many things to an image like alter brightness/contrast, smoothing the image and more. If you have your data already use Image J to improve the quality of your pictures. Start with the Beginning tutorial and then progress as required. Modify images before they go into your PowerPoint presentation. Never alter the original image! Always modify a copy and document how you modified it.

* For this activity, take images in a sequence to show sample detail. For example, take images at 500x, 1000x, 3000x. Save the images to the thumb drive and use them to create pictures in your final report.

1. Sample Prep
5. All samples MUST be dry before mounting (use a desiccator if necessary).
6. Once a sample is dry, carefully stick it to the metal stage of a mounting stub with carbon tape or carbon paste.
7. To ensure that the sample is stuck down and clean, press it gently into the carbon tape, gently blow a little compressed air across it.
8. Only samples less than 25 mm diameter x 30 mm thick should be loaded into the sample holder.

2. Loading Samples
1. Place the pin on the metal stub with your dry, stuck down sample into the hole in the center of the sample cup.
2. Place turn downed sample into the vacuum chamber and pull the door down until it is complete shut.
3. Dial down the sample so it appears to be even with the outside rim of the cup (you can check this by drawing a ruler across the top of the cup. It should not encounter your sample – if it does, dial down the sample further into the cup.
4. Once the sample is just beneath the outside of the cup, turn it down an additional four (4) clicks so that the sample is well below the metal rim.

3. Image capture (tiff) / Storage *
1. Once you have an image you want to capture (take a picture of), press “Settings” and then “Label” and use the keyboard on the screen to enter a label. This label will be applied to all the images you take so remember to change it for each sample or when you think it is appropriate. First time users should take some time to look over the “Settings” menu as it allows you to adjust image quality. To exit settings and get back to your image just press “Image” located on the green menu bar at the top of the screen.
2. Once the sample is in the Phenom, it will automatically create an optical image in the upper right-hand corner of the monitor. “Map” your sample by pressing the mapping button on the screen. Once the optical map is complete, save an image by touching the camera to the right of the mapping button. Images are saved on a USB memory stick.
3. Once your image is saved on the memory stick, you can make measurements and characterize the information saved in your SEM photomicrographs on any computer capable of showing a .tif image.
4. Once you have saved the images on a stick, you can view them on the Phenom archive screen (remember that they are digitally zoomed 4x, which is the equivalent of 4 times magnification). If an image appears too dark, simply increase the brightness by touching the brightness/contrast button. Adjust the brightness by dialing (rotating) the mouse up or down.
5. Now that you have an optical image change to SEM mode by using the toggle button. This will take about thirty (30) seconds. Once an image is made, the sample can be easily moved by simple touching the feature of interest on the screen. Use the touch screen to focus, change the brightness, magnification, and capture images.
6. Once you have an image you want to capture (take a picture of), press “Settings” and then “Label” and use the keyboard on the screen to enter a label. This label will be applied to all the images you take so remember to change it for each sample or when you think it is appropriate. First time users should take some time to look over the
Paul and Sara drew extensively on the examples provided by the workshop instructors and activities that their colleagues posted to the Media Fire website to adapt existing units of instruction to include nanoscale science and technology. They drew upon three existing units of instruction to create their unit; one was developed by one of the course instructors and refined over a three year period, another was developed by a fifteen-year veteran chemistry teacher who teaches next door to Paul in the same school and took the summer workshop with a group of teachers from the same school that Paul teaches at and the third unit was developed by Paul last year.

Paul’s Project NANO unit was designed as a stand-alone unit rather than an extension unit. Paul originally planned to teach the unit later in the academic year, following an introduction to homogeneous and heterogeneous substances. However, Paul and another participating teacher from his school agreed to schedule the Project NANO toolkit back-to-back so that the SEM would be in their school building for four weeks instead of two, thus allowing more time for students to do science fair projects using the SEM and Leica should they chose to do so (although no students did make this choice). Thus, Paul taught the Project NANO unit as the second unit he taught in each of the two chemistry classes this academic year.

**Paul’s Content Representations (CoRe) table**

During the summer workshop, Paul collaborated with two other high school chemistry teachers to discuss and fill out the CoRe table. The following is Paul’s coded CoRe table which includes a column on the right side with researcher memos and codes. This table is an example of how each of the teachers’ CoRes were coded in this study:
**Content Representations (CoRe)**

*This CoRe is designed for:* *(chemistry, sophomores)*

**Composition of Matter**

<table>
<thead>
<tr>
<th>Big Ideas</th>
<th>A: Mixtures</th>
<th>B: Solutions, colloids and suspensions</th>
<th>C: Purity of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heterogeneous vs. homogenous</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>What you intend the students to learn about this idea</th>
<th>Distinguish, characterize and classify</th>
<th></th>
<th></th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Why is it important for the students to know this?</th>
<th>Why milk is homogenized</th>
<th>Understanding purity and separation of mixtures</th>
<th>Separation of mixtures</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>What else do you know about this idea (that you do not intend the students to know yet?)</th>
<th>Homogeneity dependent on scale</th>
<th>Intermolecular forces</th>
<th>Acid and Base chemistry concentrations</th>
<th>Percent of composition</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Researchers Memos and codes</th>
<th>Characterize and classify</th>
<th>Practical application</th>
<th>Understanding mixtures</th>
<th>Scaffolding understanding mixtures</th>
<th>scaffolding</th>
</tr>
</thead>
</table>

- Homogeneity dependent on scale
- Intermolecular forces
- Acid and Base chemistry concentrations
- Percent of composition
- Percent of yield
- Electrolytes
- Distillation
- Filtration
<table>
<thead>
<tr>
<th>Difficulties/limitations connected with teaching this idea:</th>
<th>Don’t get it</th>
<th>Size</th>
<th>Hard to conceptualize as levels</th>
<th>Cannot classify</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cannot classify</td>
<td>Can’t conceptualize the difference between them</td>
<td></td>
<td>Cannot classify</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Common misconceptions students hold about this idea:</th>
<th>Solutions more than liquid</th>
<th>Black and white, looks pure</th>
<th></th>
<th>Debunking misconceptions about solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Debunking dichotomous thinking</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Difficulty/limitations connected with use of scientific instruments</th>
<th>Can’t do liquids, oils and gases</th>
<th>Atomic level</th>
<th></th>
<th>Instrument limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>What are some learning opportunities that are made possible with the use of the SEM technology</th>
<th>Can visualize, especially colloids and suspensions</th>
<th>Can visualize Quantify data</th>
<th></th>
<th>Affordances of technology</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Quantify data</td>
<td></td>
<td></td>
<td>Visual learning experience</td>
</tr>
</tbody>
</table>

*CoRE template modified from a template created by Loughran, Berry and Mulhall (2006).*
**Focused Coding of Composition of Matter Unit**

The following table contains the focused codes for Paul's CoRe. Notice that the codes are color coded, a method utilized during the data analysis phase of the research to identify relationships between codes.

<table>
<thead>
<tr>
<th>Mixtures</th>
<th>Solutions, colloids and suspensions</th>
<th>Purity of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Heterogeneous vs. homogenous</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Characterize and classify</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Practical application</td>
<td>Understanding mixtures</td>
<td>Understanding mixtures</td>
</tr>
<tr>
<td>scaffolding</td>
<td>scaffolding</td>
<td>Scaffolding understanding mixtures</td>
</tr>
<tr>
<td>Cannot classify</td>
<td>Cannot classify because of a lack of understanding of characteristics</td>
<td>Developmental limitation - Cannot classify because of a lack of understanding of characteristics as levels</td>
</tr>
<tr>
<td></td>
<td>Debunking misconceptions about solutions</td>
<td>Debunking dichotomous thinking</td>
</tr>
<tr>
<td></td>
<td>Instrument limitations</td>
<td>Instrument limitations</td>
</tr>
<tr>
<td></td>
<td>Affordances of technology</td>
<td>Visual learning experience</td>
</tr>
<tr>
<td></td>
<td>Visual learning experience</td>
<td>Quantitative reasoning</td>
</tr>
</tbody>
</table>
Here is a table that shows an analysis of which questions or prompts on the CoRe table that Paul and Sara did not address during the summer workshop nor did Paul follow up by entering call-outs in those blank cells:

**Missing Data on CoRe**

<table>
<thead>
<tr>
<th>Question</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knowledge about students’ thinking which influences your teaching of this idea</td>
</tr>
<tr>
<td>Knowledge about students’ thinking that influences how you integrate technology into the lesson</td>
</tr>
<tr>
<td>Other factors that influence your teaching of this idea.</td>
</tr>
<tr>
<td>Teaching procedures (and particular reasons for using these to engage with this idea).</td>
</tr>
<tr>
<td>Specific ways of ascertaining student’s understanding or confusion around this idea (include likely range of responses.)</td>
</tr>
</tbody>
</table>

Paul and his colleague identified three big ideas in science to focus the unit; mixtures – heterogeneous verses homogenous, solutions, colloids and suspensions and purity of samples. Using focused coding of their CoRe table, I developed two primary categories with multiple sub-categories of responses. The two categories are: type of unit and instructional strategies which I will describe in the following sections.

**Type of unit.** The first category, type of unit, is characterization and classification of matter (as heterogeneous or homogenous, and solutions, colloids and suspensions). Paul drew upon his metastrategic to develop a rationale for choosing this type of unit. He said during the summer workshop and wrote in his CoRe that although the topics in this unit are foundational concepts vital to understanding more advanced topics in chemistry, the topics are often boring for students to learn.
Paul drew upon his PCK to integrate the use of the SEM to provide a highly contextualized experience for students with a goal of improving student engagement and comprehension of complex ideas. The unit addresses students’ developmental limitations by scaffolding students’ understanding of the characteristics of different types of substances through both lectures and laboratory experiments. Paul expressed during classroom observations that for the most part, he provided content knowledge within the context of the activity stations or immediately before students began working at the stations.

The unit also includes student worksheets intended to debunk students’ misconceptions about mixtures and solutions. For example, Paul said during the summer workshop and reiterated in his CoRe at during the focus group discussion that in recognition that misconceptions are often a product of dichotomous thinking such as, “if it looks pure, it must be pure” he provided examples of practical applications of the key concepts such as exploring the difference between a mixture and solution by reading about familiar substances such as milk and why milk is typically homogenized for human consumption.

**Instructional strategies.** The second category developed from coding Paul and Sara's CoRe table is *instructional strategies*. The sub-categories of this form of knowledge within Paul and Sara's body of PCK are *integration of visual learning experiences with class lecture* and *experimentation using a guided inquiry approach*.

The unit placed a strong emphasis on quantitative reasoning; understanding the affordances of technology to examine, image and measure matter at various scales.
Paul’s lessons also involved understanding the limitations of technology and how to develop criteria for choosing the most appropriate scientific instruments for each step of making observations and building a body of evidence to support a claim or argument. In the CoRe table, the teachers also emphasized ways in which they intentionally scaffolded the delivery of knowledge and development of skills throughout the unit.

Missing from Paul’s CoRe developed in the summer are ideas related to knowledge about students’ thinking which influenced his own thinking about how to teach the topics in the unit and how to integrate technology into the lesson. Nor did Paul address ideas regarding ways of assessing for students’ understanding, lack of understanding, alternative ideas or misconceptions about specific topics.

Paul’s Knowledge, Skills, Experience, Community, Assessment Scoring Guide scores. The unit of instruction that Paul and Sara developed was scored using the Evaluation Criteria for Science Inquiry/Engineering Design Curriculum Unit scoring guide (see Appendix E). The following Table A.1 shows the scores assigned to each curriculum unit and the total score:
Table A.1
Cumulative scores for each curriculum element in Paul's unit

<table>
<thead>
<tr>
<th></th>
<th>Knowledge and Concept</th>
<th>Science Inquiry Skills</th>
<th>Student Experiences</th>
<th>Learning Community</th>
<th>Assessment of Student Achievement</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Possible points</td>
<td>12</td>
<td>15</td>
<td>12</td>
<td>12</td>
<td>15</td>
<td>66</td>
</tr>
<tr>
<td>Paul’s score</td>
<td>11</td>
<td>13</td>
<td>6</td>
<td>10</td>
<td>11</td>
<td>51</td>
</tr>
</tbody>
</table>

The unit scored well in the Knowledge and Concepts curriculum element earning a total of 11 points in the category. The unit scored all of the possible points for appropriate grade level, conceptual knowledge organized around a big idea in science, clear expectations stated in student friendly language, and state science grade-level standards explicitly embedded in the unit. The unit lost one point for new conceptual knowledge introduced with conceptual links because although there was some language about how the unit fits within the larger lesson cycle, this description mostly focused on later learning targets instead of prior learning targets.

Again, the unit scored all of the possible points for science inquiry skills including students generate testable and appropriate science inquiry that uses the targeted science content, students identify variables and develop inquiry designs and data collection protocol(s), students present and critically evaluate their empirical data and results and students employ appropriate technology when conducting their investigation and presenting their findings. The unit lost two points for students make and defend knowledge claims from critical analysis of their science
inquiry because the student directions for the final defense asked students to present knowledge claims but not publicly defend their arguments. Instead, students were asked to individually defend knowledge claims in their work packet worksheets.

The unit received low scores for three out of the four curriculum elements in the Student Experiences section. The unit received one of three points for accommodates student diversity in strategies, approaches, abilities, cultural perspectives and learning styles due to a lack of any specific differentiation strategies listed in the unit. Indeed, classroom observations supported this low score in that the only observable differentiation strategy employed in the unit was that the laboratory stations included activities that varied in terms of the level of cognitive demand with some requiring higher order thinking skills such as critical thinking and problem solving and other stations requiring the use of lower order skills such as memorization and recitation in preparation for application of content knowledge and skills in the inquiry process. The stations that required a higher level of cognitive demand were placed near the SEM so that Paul could interact with and support students at those stations while remaining attentive to groups of students at the SEM.

The unit scored one of three points on facilitates the use of meta-strategies to identify, monitor and regulate learning due to a general lack of formative assessments and an emphasis on summative assessment at the conclusion of the unit. The unit scored a one of three points on students are prompted to pursue extensions and/or additional investigations because the only mention of extensions in the student work packet and classroom observations was related to encouraging students to draw upon the SEM for science fair project with no specific examples of possible extensions provided.

The unit scored well on the Learning Communities section scoring three of three points on three of the four curriculum elements found in that section. The areas that received this high
score include *engages students in activities or discussions that draw out what they know and how they know, working in collaborative groups to plan and execute the inquiry and students are encouraged to share inquiry ideas and resources with the full class*. However the unit scored one of three points on *students communicate and defend the results of their inquiry to their instructor and peers*, again because the students were asked to present their data but not to defend their results before their peers.

In the final section of the scoring guide, the unit received three of three possible points for three of the curriculum elements; *providing students with multiple chances to revise their thinking, the assessment provides an inventory or post-assessment of knowledge and involves students in developing work samples that demonstrate the achievement of knowledge and skills learning objectives through science inquiry experiences*. However the unit scored zero of three points due to the lack of assessments of students’ prior knowledge of targeted concepts and skills and two of three points for including few opportunities for students to self-assess misconceptions and learning. It was noted that although the unit he developed in the summer did not include formative assessments, and therefor he received a zero score on the initial unit plan submitted at the conclusion of the workshop, Paul told the researchers following the first classroom observation that he added formative assessments just before actually teaching the unit.

**Paul’s Pre and Post Survey Scores.** Content-based pre and post surveys were administered at the beginning and end of each of the three respective summer workshop. Each survey was scored after class on the same day that the survey was administered using a locally developed rubric (see Appendix G) that has a three point scale with one being the lowest score meaning weak or no evidence, two meaning emerging and three
meaning proficient. The following table A.2 presents Paul’s pre and post survey scores. These data inform the sub question *do teachers demonstrate scientific content knowledge gains in response to the 2012 Project NANO summer workshop?*

**Table A. 2**

**Paul's Pre and Post Survey Scores**

<table>
<thead>
<tr>
<th>Pre – Post Survey Questions</th>
<th>Pre Survey</th>
<th>Post Survey</th>
</tr>
</thead>
<tbody>
<tr>
<td>What is the difference between an optical microscope and an SEM”</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Describe 5 key components of the scanning electron microscope (the mechanics of the tool)</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Describe safety protocols related to working with secondary level students and a table top SEM</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Provide a brief description of how you might integrate optical and electron microscopes in a course to instruction students on form and function related to the discipline you teach.</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

Paul scored two points on both the pre and post survey question *what is the difference between an optical microscope and an SEM* because he was able to describe that the optical microscope uses light and an SEM uses electrons to gain a “much deeper optical magnification” however he did not specify that the electron wavelength is much shorter than proton (light) wave lengths and that is the reason that the electron microscope provides a higher level of magnification in grey scale images using an electromagnetic lens.

Paul scored two of three points on the pre-survey question *describe 5 key components of the scanning electron microscope (the mechanics of the tool)* because he
was able to list four part of the SEM using vague terms, only three of which generally described parts that are specific to the operation of an SEM. On the post survey Paul scored three out of three points because he was able to describe five features using correct terminology to describe parts of the SEM.

Paul received zero points on the pre survey question describe safety protocols related to working with secondary level students and a table top SEM because he did not answer the question, however he scored two of three points in the post survey because he listed standard lab safety protocols, and two specific SEM safety protocols but did not list the log book used to track when the SEM malfunctions and the necessity for constant adult supervision at the SEM.

Paul’s post survey score jumped from two points on the pre-survey to a score of three of three points for the last question on the survey provide a brief description of how you might integrate optical and electron microscopes in a course to instruction students on form and function related to the discipline you teach. Paul wrote that “classification of matter works well and gets into atomic level form and function a key indicator for high school science listed in A Framework for K-12 Science” (2011).

Classroom observations. Here I provide a summative overview of the classroom observations using the EQUIP observational prompts and scores and discuss evidence of Paul’s thinking. Three classroom observations were conducted in Paul’s ninety-minute, second period chemistry class comprised of primarily so-called high-ability level students and one observation was conducted in Paul's so-called low-ability level, third period class. Recall that each of Paul’s two classes were grouped into so-called high and low
ability levels (as described by the school district). I begin by describing three classroom observations in the so-called high-ability level classroom and then describe one observation conducted in the so-called low-ability class.

Recall the EQUIP classroom observation protocol provides a summative scoring guide for each observation that ranks the level of inquiry as follows. Level 1 - Pre-inquiry, level 2 - Developing Inquiry, level 3 - Proficient inquiry and level 4 - Exemplary inquiry. The Electronic Quality of Inquiry Protocol (EQUIP) instrument validation study (Marshall, Smart & Horton, 2009) indicates that it is usually the case that the first day of any unit of instruction is primarily dedicated to pre-inquiry activities such as a lecture describing the learning outcome objectives, framing a general sense of what will happen during the unit and introducing foundational concepts that will be explored throughout the unit. The first classroom observation took place on the first day of the Project NANO unit and true to form; the class period was mostly focused on level 1, pre-inquiry and level 2, developing inquiry activities.

During the second classroom observation, Paul mentioned to the researcher that students in his so-called low-ability level class responded quite differently to the activities in the unit than his so-called higher ability level class of students. He observed that by the third day of the unit, students in the so-called low-ability level class failed to engage in the activities and that formative assessments indicated that students were not making connections between the purpose of each activity and the purpose of overall

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2 Please note that the terms “low-ability” and “high-ability” groups are designated by the school districts as the result of mathematics tests administered at the beginning of each school year and are not designations assigned by the researcher to describe classes of students.
lessons. He stressed that the level of engagement and critical thinking connecting concepts to the big ideas was much greater in high-ability group class of students. During the classroom observation, Paul expressed surprise and concern about this difference in the level of student engagement. He echoed this sense of surprise in his call-outs and during the focus group discussion, especially since he had included prompts in the student worksheets specifically intended to involve students in group discussions designed to assist all group members with making connections between the content addressed in the activities and the big ideas. When asked following a classroom observation about differentiation strategies he was considering or using to address the discrepancies between the two classes of students, Paul said that since he was mostly “strapped to the SEM” he hadn’t figured out a way to change the unit for struggling learners “on the fly” and that he planned to work on figuring this out after the conclusion of the unit when he could work with his coach “to step back and look at the overall picture and figure out new ways to accommodate the different needs of students”.

The laboratory activities on the first day of class were observed to be primarily focused on building foundational knowledge by defining what is meant by intensive, extensive, physical and chemical properties of matter. For example, one laboratory activity was focused on characterizing a variety of materials (hand samples), thus there were a limited number of correct responses and the inquiry was very much in the pre-inquiry and developing inquiry stage. Overall, the first observed lesson was characterized as a level 2 – developing inquiry lesson with a strong focus on providing an overview of the unit and on memorization of facts.
The second observation was conducted two days later. The focus of this lesson was on understanding classification of matter; compounds and pure substances. The entire class was dedicated to a classroom lecture and a Powers of Ten video. This lesson was characterized as a level 1 – pre-inquiry experience, which the teacher repeatedly said involved delivering foundational knowledge to be memorized and used to do the inquiry project that would begin the following week. The exception is that when students asked questions during the lecture, the teacher worked to engage the entire class in choral responses and occasionally probed with low-level questions to make sure that students understood the topic.

The third observation of the so-called high-ability level chemistry class was conducted on a Monday as students were settling back into school after a three-day weekend. This lesson was dedicated to having the class divide into groups with students they did not already know. The teacher then led the entire class through the sample preparation for both the SEM stubs and the wet-mount slides for the Leica. He then introduced the stations providing directions using information found in the student work packet to visually guide students through each station activity. With twenty-minutes remaining in the class, he began the first rotation of stations.

At the SEM station, the teachers worked with the first group to model and verbally explain how to load the samples into the SEM, label the images, raster the image to give the instrument information on the edges of the sample and how to work the instrument controls in the SEM mode. The SEM was hooked up the overhead projector so that all of the students in the class could see the SEM images.
The fourth observation of the so-called high-ability level class was conducted on the final day of the unit. Half of the class period was dedicated to discussion in response to the daily question and to group presentations. The other half of the class period was dedicated to the summative unit examination. Although the daily question “discussion” was primarily conducted as a choral response exercise, two students in the class asked a series of questions that prompted a discussion between the teacher and these two students. This discussion provided the teacher with the opportunity to address scientific misconceptions he had noticed in the student work packet responses related to the difference between mixtures and colloids. Although both this classroom discussion and the format of the group presentations was very prescriptive, the lessons did involve what the teacher described following this classroom observation as a seamless integration of the content and the big ideas related to composition of matter. The teacher was the only person in the room that asked students to defend ideas presented by each group, thus the teacher’s intention of formatting the presentation assignment to promote active learning on the part of the audience as well as the presenters was not realized. The students in the audience appeared to be confused about how they should respond and often followed the choral response pattern when the teacher asked for input from the audience.

In addition to the four observations conducted in the so-called high-ability group class, one additional observation was conducted in the so-called low-ability group class near the end of the unit. Recall that the third period class is comprised of so-called low-ability level students, 75% of whom are on an individualized educational plan (IEP) for a variety of special needs. The level of student engagement observed in this class was
markedly lower than that of the so-called high-ability level class. In nearly every group, only one or two students out of four group members was actively engaged in preparing their reports and PowerPoint presentations. With the exception of the students on the SEM who were working with the teacher, at least half of the class was off-task throughout the class period.

After class, the teacher shared that because many of the students use their time inappropriately, groups were scrambling to complete the station activities “at the last minute”. By this point of the unit, Paul felt pressure to move each group quickly through their time on the SEM to ensure that every student got a chance to get on the instrument two-times. Thus he felt that he had moved from a thoughtful facilitative approach to one that was increasingly more directive and focused on memorization of facts rather than a student inquiry-driven exploration. Paul emphasized that this was exactly the opposite of what he had intended during the unit planning phase when he and Sara wrote that the first experience on the SEM would involve learning the basic terminology and concepts as well as how to use the controls and the second experience was meant to involve higher order thinking skills such as critical thinking to categorize samples based on particular characteristics student observed.

In comparison to the second period class, Paul felt that this group of students in his third period class may have engaged more deeply with the topics on the unit if they had more time to “play with guidance on the SEM”, but given the 20-minute rotation cycle and the fact that many students had not acquired images necessary for their presentation by the end of their first rotation on the SEM, he said in his call-outs, during
the focus group discussion and following the classroom observation that he decided to move groups through quickly through their second rotation to ensure that everyone captured images for their presentations rather than allowing time for “free play” and discussion that may have led to deeper integration of concepts. Paul expressed after class that because the students had fallen behind in this third period class, he especially didn’t have time to think about how to improve upon the experience for these students in the way that he did for his so-called high-ability class because students needed to “quickly get through the unit and be prepared to move on to the next unit”.

Interestingly the Instructional Assistant (IA) in the so-called high-ability level class was much more engaged in ensuring that students understood the purpose and steps involved in each of the stations than the IAs were in the so-called low-ability level class. Whereas the IA for the so-called higher ability class was scientifically trained, the so-called low-ability class had a different IA nearly every day, none of whom claimed to have scientific training when asked by the researcher. The teacher shared after a classroom observation that he thought that the extra assistance in the second period, so-called high-ability level class was a contributing factor to students’ level of engagement and the lack of assistance in the third period so-called low-ability class contributed to the students’ lack of engagement, sense of knowing exactly what to do at all times and teachers’ sense of frustration at being “stuck at the SEM through the entire period when kids obviously needed some guidance to stay on task.” Based on the that students frequently went off task and got behind in the schedule, the teacher said that he perceived the need to turn to a more directive approach to working with the students during the
movements that he was able to move away from the SEM, which in turn impacted students’ attitudes about the topic and their ability to learn.

During the focus group, Paul expressed that taking out the “free play time” for the third period class who fell behind in their station rotations defeated a major purpose of including the SEM in the unit and that he needed to figure out a better way of meeting the requirements of special needs learners. He acknowledged that the scientifically trained IA made a significant positive difference in the so-called high-ability class, but he remained unsure about the value of spending time to prepare any of the IAs to assist with labs in the future since the IAs tend to frequently rotate to different classes and are an inconsistent source of support.

**Evidence of changes in Paul’s thinking**

During the focus group and personal conversations that took place before and after the classroom observations, there were several instances where Paul explicitly mentioned changes in his thinking. These changes related to both practical changes he would make to improve students’ experiences with the technologies used in the unit and pedagogical ideas related to how he plans to scaffold instruction next time. The following data table A.3 informs the first sub-question, *how if at all, does teachers’ metastrategic thinking and PCK change between the summer workshop and the reflection period following the implementation of the Project NANO unit?* Because the sources of the data included both coded transcripts and informal comments captured in fieldnotes, I do not have verbatim quotations to support each category. Therefore, I chose to be consistent throughout the table by paraphrasing Paul’s ideas that communicate his PCK.
Table A.3

Evidence of changes in Paul's Metastrategic Thinking & PCK

<table>
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<tr>
<th>Challenge or limitation</th>
<th>New Metastrategic Thinking &amp; PCK</th>
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<tr>
<td>He wonders if the unit he taught was giving the students too much independence before they were ready and if his students would benefit from a more guided or even “canned” laboratory experiences while they are learning basic laboratory procedures and content knowledge.</td>
<td>Design a new set of simple laboratory activities drawing on simple and familiar substances to demonstrate the big ideas included in the unit and then move to the inquiry unit using the SEM. He thinks that a guided experience will provide a foundation of knowledge that will enable students to be able to work more independently with the SEM and especially to be able to navigate the other stations when he is “stuck” at the SEM.</td>
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<td>He did not know how to plan for the significant increase of the class size this academic year when he was planning his unit last summer.</td>
<td>He chose to increase the size of each group to accommodate for this change in class size. He related on multiple occasions that he thought that larger group sizes may have led to a number of members of the group “checking out” and allowing one or two people in the group to do most or all of the work and the thinking. Next year, he plans to have two of each station so that he can keep the number of students in each lab group limited to two or three student each and then work with each group to establish explicit roles and responsibilities to ensure that each member is “pulling his or her own weight” throughout each of the laboratory and report writing steps.</td>
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<td>Paul questioned the educational value of having the students provide classroom presentations. He said that for the most part, each group of students would present on the same ideas and that for this reason, the majority of the audience “checked-out” after the second or third presentation. Paul questioned the wisdom of dedicating three full class periods to preparing to present and half a period for the presentations themselves.</td>
<td>After hearing the rationale of other teachers who discussed the benefits of moving to a gallery walk format during the focus group discussion, Paul said that he is considering either a gallery walk with question prompts as an alternative approach to sum up the unit or “flipping the unit” and having students load their presentations onto a class website, having students watch these at home and come prepared for roundtable discussions on the presentation in class.</td>
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During the focus group, Paul pointed out that the majority of the groups each brought the same item (hairs, erasers and parts of pencils). Paul thinks that he will do two things next year to prevent this replication; he will provide samples for those who either forget to bring in a sample or find that their sample is somehow inadequate and he will narrow the choices of types of samples that students may bring in rather than leaving this choice completely up to the students.

The researcher noticed that in both the second and third period classes, the majority of the student had forgotten to bring samples to class. When they read the list of daily learning targets on the white board at the beginning of class, students scrambled to pull out their own hair, create pencil shavings and find anything at hand that would do. The teacher acknowledged that this may have been due to the fact that the students were just returning from a three-day weekend and had forgotten the assignment due to the long gap between classes. Next year, Paul said that if he does ask students to bring samples, he will assign this to be done mid-week on the week prior to the arrival of the SEM to ensure that students have a chance to “clear their sample” with him and make sure that it is one that is likely to work with the SEM.

Paul was concerned that the pressure of capturing images with the SEM for the presentation took precedence over taking time to explore and interpret materials with the microscope and that at least half of the members in the so called low-ability level class and several students in the so-called high-ability class failed to deeply engage in creating the presentations or fully participate in scientific discussions. Paul is seriously considering finding another forum for students to share and discuss their ideas in a way that they can develop their scientific argumentation skills to defend and justify claims by drawing on evidence. He has not yet decided what that alternative forum will be, but says that whatever he chooses will be less time consuming and will ask students to draw on higher order thinking skills rather than sticking with the memorization and recitation mode.

In keeping with earlier reflections, Paul concurred with the rest of the teachers in the focus group that he needs to include more opportunities for students to connect the concepts covered in the laboratory station activities to the big ideas in the unit. He found that most of the students with “low level abilities” seemed to operate on the level of

This summer, Paul plans to take a follow-up Project NANO workshop where he would like to have assistance in developing daily exit survey questions that students will discuss in their lab groups at the end of each class period. He will then ask each student to submit their answers in writing to ensure that learners have the opportunity to receive timely feedback from the
lower order thinking and were unable to extrapolate knowledge using higher order thinking skills such as critical thinking and problem solving.

teacher to help them discover misconceptions they may hold and to discuss ideas students find to be confusing the next class period. In this way, Paul feels that he will be able to gather information necessary to inform changes to his lesson plan for the next day. He claimed that since he was “stuck” at the SEM and unable to circulate throughout the other stations during the class period, he was unable to change the lessons “on the fly” during the class period and unless he is able to figure out another solution, this is the best formative assessment strategy he can think of to negotiate timely changes to the lessons in response to student feedback.

Despite his limited experience as a high school level teacher, there are many instances where it is apparent that Paul drew upon his metastrategic knowledge to inform his choices as to which strategies to draw upon from his repertoire of PCK. For example, during the initial planning, he structured each laboratory station to involve explicit logical connections between one another and wrote prompts in the work packet to guide student exploration of the connections between discrete concepts and the big ideas. As mentioned above, he also reflected on strategies to include the next time he teaches the unit to make these connections even more explicit throughout the unit, which speaks to the sub-question related to how Paul’s PCK changed over time.

Paul related during the workshop, in his CoRe and unit plan and during the classroom observations and focus group discussion that he carefully considered what foundational information to present in a class lecture and then selected out ideas for students to engage with and discover on their own, thus scaffolding the student's thinking in such a way that empowered students to engage their minds on a higher order level of
thinking. During classroom observations and follow up conversations with the researcher, Paul described his process of carefully choosing when to ask questions, when to let students explore and struggle to conceptualize new ideas and how to redirect thinking with gentle “nudges” rather than “giving it all away for nothing”. Paul also expressed a profound sense of frustration that he was often only able to provide this careful guidance to students at the SEM while the rest of the students struggled at the other lab stations.

Interestingly, Paul did not address many ideas related to student thinking that influenced his thinking in the CoRe nor in his unit of instruction. He scored only six out of twelve possible points on the unit of instruction section related to student thinking. The primarily way in which he did describe his knowledge of student thinking was simply to say that he chose to integrate the SEM into teaching this particular topic because although the topic is foundational to the discipline of chemistry it can be a rather boring and dry topic. He said that including the SEM may help to make the topic more interesting and therefore more engaging for learners.

Throughout each of the classroom observations, Paul did not appear to have a sense of how to anticipate student thinking throughout the lesson, although this was probably due in large part to the fact that he was unable to circulate around the classroom and listen and respond to the lab group discussions. At one point, Paul said to the researcher that he finds it to be too difficult to change a lesson “on the fly”. Again, this may be due in part to the fact that he is novice teacher who planned the majority of the unit working with Sara, a pre-service teacher, and that both Paul and Sara are still
learning about student thinking related to learning specific topics. However, Paul shared in his call-out reflections that the question on the CoRe, *what else do you know about this idea that you don’t intend students to know yet* assisted him to think about what “I would consider to be a deeper level of understanding and larger interconnected ideas that would build off of these initial concepts”. Thus, Paul provided some insight as to how he negotiated scaffolding the learning, which speaks to the research question that asks how he negotiated the inclusion of novel science content and technology into the curriculum.

Paul mentioned several technical issues that also relate to student thinking that he felt better prepared to solve now that he has taught the unit this year. The following table A.4 lists issues Paul described and his strategic response to address those issues.

**Table A.4**

**Paul's Metastrategic Thinking & PCK Related to Technical Challenges & Responses**

<table>
<thead>
<tr>
<th>Technical Challenges</th>
<th>Paul’s Strategic Response</th>
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<td>Paul noticed that after the first day of looking at the SEM images on the overhead screen without any opportunity to discuss and interpret those images, students in both of his classes seemed to have “gotten burned out on the SEM images”. Paul expressed surprise in that each subsequent lab group that used the SEM seemed to be less excited than the last and he attributes this decline in interest in part to the projection of the SEM images on the overhead screen.</td>
<td>He decided that he will not include this overhead display of the SEM screen next time he teaches this unit.</td>
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Paul thinks that another reason that students did not engage with the SEM in the way he expected is that many of the students failed to grasp the conceptual distinctions between solutions, mixtures and colloids. Thus experiences on both the optical and electron microscope were frustrating to many students because they either didn’t understand the purpose of the activity or they did understand the purpose but were unable to perform the tasks they were assigned to complete.

He decided that negotiating new terminology and complex concepts while at the same time attempting to categorize substances using very unfamiliar technology was too much for some of the students, especially those with learning disabilities and for some of the ESL students who struggled with the terminology. He decided that next time he will teach a preparatory unit to the composition of matter unit so that all students are well versed in the basic concepts and terminology used to describe composition of matter (homogenous and heterogeneous substances, purity, mixture, solutions and colloids) prior to working with the SEM and Leica.

Another technical issue that Paul addressed is that many students forgot to bring in a thumb-drive so he loaned out his own and therefore he had to spend time each evening emailing images to each group. This may appear to be a small issue, however given that he scheduled the class to have 20-minute rotations between stations, every moment spent negotiating issues to do with the thumb drive was another moment lost on the SEM. Plus, the hours spent emailing images to groups meant that he had less time to reflect on student work and consider differentiation strategies in response to student thinking.

To solve this problem next year, Paul asked Project NANO to provide a set of numbered thumb drives that are known to work with the SEM so that student may simply capture their images and immediately thereafter download images from the thumb drive to their own file in a class website. This request has been met and three numbered thumb-drives on lanyards have been added to the toolkit.

Time lost at the SEM wasn’t the only concern since students ran into difficulties at the other stations that wasted time as well.

Based on his experience, Paul now recognizes the causes of these delays and has created a plan for how to remove these obstacles. Paul plans to speak with the school district about updating the laptop computers so that students aren’t waiting ten to fifteen minutes for computers to open software programs and thus missing most of the time dedicated to stations that involve those laptops. He also hopes that the school district may be able to remove firewalls from certain websites so that he doesn’t have to repeatedly ask the group at the SEM to wait while he goes to enter his password every time the computer goes to sleep when the groups rotate.
In addition to addressing technical limitations, Paul has now developed new PCK to be more responsive to student needs, thus positively informing the research subquestion *do teachers demonstrate scientific content knowledge gains in response to the 2012 Project NANO summer workshop?* For instance, he now has ideas related to problems students had with understanding the idea that highly conductive materials move electrons around so that they tend to build up or “charge” more slowly than less conductive samples such as organic materials. Paul reflected in his call-outs that he attempted to use the SEM in a novel way by using electron charge as a way to identify if a substance resisted electrical conductance (and therefore was most likely non-metal). However, because electron charges built up on samples that he did not expect to charge as much as they did, he found this approach to substance classification to be a misleading or unreliable approach to classifying matter. He said that if the SEM had an elemental analytics capacity, this would be a great piece to add to his unit, but since the model provided through the program does not have this capacity, this idea turned out to be confusing to students and not something he will try again with this particular instrument.

Paul’s reflection indicates that he demonstrated scientific content knowledge gains in that he is now aware of some of the limitations of this particular model of SEM and has developed a better understanding for how to approach the topic of conductivity and classification using the instrument. Although this particular gain did not actually occur immediately in response to the summer workshop, Paul’s response indicates that one of the ways in which he negotiated the integration of novel science and technology into the curriculum is that he set a learning goal for himself by developing a testable
scientific question related to how the SEM may be used to classify matter. By gathering data throughout the implementation of the unit to inform his question, he increased his scientific content knowledge and changed his metastrategic thinking and PCK.

**Summary of How These Evidence Inform the Research Questions**

It is interesting to reflect upon the extent to which Paul’s PCK and metastrategic thinking is related to the fact that he is a novice teacher in the second year of teaching chemistry at the high school level. Although Paul has recent experience teaching entry-level college chemistry, he expressed his own awareness of his limited PCK for teaching high school level chemistry. He clearly articulated some of his strategies for building his PCK to meet the challenge of developing and implementing his Project NANO unit of instruction during and after classroom observations, in his CoRe and call-outs and during the focus group. These data informs the research question, *how do teachers negotiate the inclusion of nanoscale science and technology into the curriculum?*

Paul chose to focus on the big idea of nanoscale science, structure of matter, by drawing extensively upon ideas provided by colleagues including the course instructors and peers. Again, he shared that he chose a fundamental topic in science, composition of matter, which he thinks are typically boring to learn but that could potentially be made more interesting to students by incorporating high powered microscopy into the unit. These two metastrategic decisions inform the research sub question, *of the nine “big ideas” in nanoscale science and technology, which are the big ideas that teachers choose to teach in their Project NANO unit and why?*
According to the results of the EQUIP observations, the lessons in the unit were at the level of “developing inquiry”. Paul’s unit used a fairly prescriptive approach to exploring the big ideas related to composition of matter. Rather than using an interactive writing strategy or another instructional technique that engages students in higher order thinking, the student packet he provided restricted students to write fill-in-the-blank-type rote responses. Although he did endeavor to introduce student choice into the unit by allowing lab groups to select their own samples to examine, scientific procedures were highly proscribed in a step-by-step manner. Although he intended for students to engage in scientific argumentation to defend knowledge claims, the choral response approach he used throughout the unit set a pattern of response for the student that they rarely deviated from during the classroom observations. It is not clear to the researcher that Paul is aware that the emerging classroom culture he is creating of call and choral response is influencing the degree to which his students feel empowered to ask questions of their fellow students on their own, especially in a whole-group situation. So in this particular regard, it is unclear to the researcher whether or not this aspect of Paul's PCK changed between the summer workshop and the reflection period following the unit implementation.

Paul’s unit design was obviously heavily influenced by proficiency-based education strategies required by his school district. For instance, each day Paul posted the lesson learning objectives that he explicitly addressed at the beginning of each class period. There are also several examples of how he incorporated teacher modeling of activities into the unit both in writing and through class demonstrations, another
proficiency-based education teaching strategy emphasized in his district. For example, in the student work packet that he developed for the unit, he included a completed data log to demonstrate the types of observations and terminology that should be used by students in their own data logs. As each group of students approached the SEM for the first time, Paul modeled how to load the samples and work the controls of the instrument. He also modeled language used to describe the samples throughout the first of two times the students used the instrument. The second time that each group approached the instrument, Paul was observed to step back to allow the students to assist one another to manipulate the instrument and capture images. This was especially true of groups that were more-or-less on task and had not fallen behind in capturing useable images during their first rotations on the SEM. Paul relied more on questioning probes to guide students rather than direct instruction for most of the groups on the SEM. Again, this is a proficiency-based education approach strongly emphasized in his school district.

Paul expressed that following this unit, he gained a better sense of how to demonstrate the use of the SEM and the Leica microscope and how to gauge the degree of assistance each group of students needed in order to be successful on each instrument. Thus informing the sub question, how, if at all, do teachers’ metastrategic thinking and PCK change between the summer workshop and the reflection period following the implementation of the Project NANO unit?

Paul’s case is a significant one, because his experience typifies the struggles of several of the teachers in Project NANO, particularly the novice teachers and teachers who reported in the pre survey that they do not typically teach using digital scientific
instruments. First, Paul worked to conceptualize how to structure an inquiry based experience for students, however he felt restricted by both his lack of knowledge of student thinking about composition of matter and being “stuck” at the SEM so that he could not circulate around the other stations to both learn about how students were thinking about the content and procedures addressed through the activities and assist the development of their thinking. Second, based on his experience in the summer workshop, Paul drew extensively upon the resources provided through the program and his peers and then integrated his own novel approach by exploring the potential of classifying substances based on how much electron are either dispersed or charge. Thus he navigated the integration of novel science and technology into the curriculum by designing both a pedagogical experiment and a scientific experiment into his unit. And finally, as Paul’s own content knowledge related to nanoscale science and technology expanded, the data he collected informed changes in his thinking about how to approach both the instructional and scientific aspect of the unit next year.
APPENDIX B

CASE-BY-CASE STUDY OF FOUR TEACHER PARTICIPANTS: TIM
Tim

Tim (pseudonym) has taught high school physics, AP physics and engineering for seven years. According to his pre-survey responses, prior to becoming a high school teacher, he worked as a professional structural and mechanical engineer for over twenty years. Tim had extensive experience working with nanoscale science and technology in his former profession as an engineer. He teaches science as inquiry and engineering design using digital and analogue scientific instruments including tools that he brought to the classroom from his former career.

In addition to his prior exposure through his earlier career, Tim is one of only three teachers out of the 23 participants who had prior exposure to the use of an SEM in a teaching and learning environment. Tim teaches in the same high school as that of one of the summer workshop co-instructors who is also his Project NANO coach. Prior to taking the summer workshop in 2012, he observed students in the Project NANO co-instructor’s own high school chemistry and advanced placement chemistry classes using the SEM over a two-year period. Tim also participated in a Project NANO, SEM demonstration at a Murdock Partners in Science conference in 2011 where he had the opportunity to manipulate the instrument used in Project NANO and discuss ideas for applications of the SEM in high school science with college level disciplinary faculty and the Project NANO Teacher on Special Assignment. The researcher had no prior relationship with Tim.
Tim’s Unit of Instruction

Tim designed his Project NANO unit for two engineering classes. The engineering classes are part of the national Project Lead the Way program, an innovative program that engages students in activities, projects and problem-based learning experiences wherein students design, build, discover, collaborate and solve problems while applying what they learn in math and science. Tim’s two engineering classes are comprised of twenty-two and twenty-four students respectively. The students are mostly seniors in high school with just a few juniors in each class. Tim taught the unit in February, well into the academic year. Thus he reported during the first classroom observation that the classroom culture for each class of students was well established by that point of the year and that students had experienced numerous activities that required the use of technology to make and record scientific observations using the language and procedures of engineering design working in a highly independent manner.

During the summer workshop, Tim experimented with SEM to capture images of dye-sensitized solar energy cells, however upon realizing that it is difficult to capture quality images of solar cells on the Phenom SEM, he was observed to quickly switch his plan. Instead, he designed a unit on material strength and how materials used for bridge construction break (compression, tension, various types of fracture and sheer). The general structure of the unit is a comparative investigation of materials.

Because Tim was the only physics and engineering design teacher enrolled in the third section of the summer workshop, he did not partner with any participants in the course to develop his unit, nor did he report drawing upon resources from the Project
NANO Media Fire website. Instead, the images and unit plan that Tim posted to the Media Fire website address a gap in the Project NANO set of instructional resources by offering participants engineering design ideas with clear links to the Project Lead the Way high school curriculum. Although Tim didn’t collaborate in a group or team to develop his unit, he did draw upon many of the instructional practices described and modeled throughout the summer workshop, including classroom management strategies and consistent use of terminology which I will describe below.

The unit involved examining brass and aluminum with the SEM and Leica and comparing images of these materials with images of wood and ferrous copper and steel captured with the Leica, optical microscope. During the summer workshop he prepared the lesson by examining metal samples he had broken in a variety of ways using a stress/strain analyzer that he has in his classroom. This machine pulls metal apart (stress) and measures the amount of force applied before the material fails (strain). Here is Tim’s unit of instruction:

**Unit Title: Strength and structure of materials**

**Knowledge:** Please use the provided space to describe the knowledge outcomes you anticipate addressing in your unit.

<table>
<thead>
<tr>
<th>Knowledge Outcomes:</th>
<th>Linked Standard (if appropriate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td></td>
</tr>
<tr>
<td>1. I can explain the difference between a SEM and a light microscope</td>
<td></td>
</tr>
<tr>
<td>2. I can safely operate the Structural Stress Analyzer SSA 1000 including:</td>
<td>H.1 Structure and Function</td>
</tr>
<tr>
<td>1. Performing tensile strength test</td>
<td></td>
</tr>
<tr>
<td>2. collecting data essential for analysis</td>
<td></td>
</tr>
<tr>
<td>3. Analyze data. Compare data to identify appropriate applications of</td>
<td></td>
</tr>
</tbody>
</table>

...
tested materials

Structure of matter
1. I can describe how tensile strength, ductility, shape and mass-distribution affect the physical properties of a material.
2. I can define stress, strain, compression, tension, brittleness, and toughness with respect to the strength of a structural member.
3. I can begin to infer how the structure of matter affects the characteristics of the properties of the material.

Interaction and change
1. I can interpret a stress/strain curve and explain the various parts and the implications of changes of shape of the curve as it relates to an object under stress.

Engineering
1. I can explain the engineering design process and how technology can be used to improve the outcome in the design-phase.

Skills: Please use the provided space to describe the skill outcomes you anticipate addressing in your unit.

<table>
<thead>
<tr>
<th>Skill Outcomes:</th>
<th>Linked Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Interpret stress/strain diagram</td>
<td>H.2 Interaction and Change</td>
</tr>
<tr>
<td>2. Operate an electron scanning microscope</td>
<td>H.2 Interaction and Change</td>
</tr>
<tr>
<td>3. Operate the SSA 1000 stress strain tool</td>
<td>H.2 Interaction and Change</td>
</tr>
<tr>
<td>4. Develop competence in engineering design process</td>
<td>H.4 Engineering Design</td>
</tr>
</tbody>
</table>

Experiences: Please use the provided space to describe the experience outcomes you anticipate addressing in your unit.

<table>
<thead>
<tr>
<th>Experience Outcomes:</th>
<th>Linked Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physically experience the different stresses and strains that exist in a bridge (kinesthetic activities)</td>
<td></td>
</tr>
<tr>
<td>Destructive testing of a metal dog-bone. Includes collection of data and development of stress/strain diagram.</td>
<td></td>
</tr>
<tr>
<td>Reflect on how technological advances allow us to make valuable predictions in engineering design</td>
<td></td>
</tr>
</tbody>
</table>
Prepare a sample for evaluation under a light-microscope and a SEM
Collect data/images using the light-microscope and SEM
Make connections between observations on SEM and the implications of a materials' strength characteristics

**Assessments:** Please use the provided space to outline and describe (in as much detail as possible) the assessments you anticipate using during your unit.

**Assessments:** Please feel free to attach drafts of these assessments if they are available.

**Informal assessments:**
Worksheet of stress/strain calculations
Proficiency assessment of use of SSA 1000 and Phenom SEM

**Formal Assessment:**
Students will complete final assessment consisting of annotated stress strain curves for aluminum and brass from their destructive testing.
Students will include SEM images of each material at 3 different magnifications (3000x, 7500x, 15000x recommended)
Students will comment on structure in images and describe from their observations how the nano-scale structure of metals relates to the macro-scale strength properties.
Students will reflect on how stress/strain data and SEM images may be used in engineering design and failure analysis.

**Pedagogical Strategies:** Please use the provided space to outline and briefly describe the pedagogical strategies you anticipate using during your unit.

**Pedagogical Strategies:**
Classroom discussion: Leading question: What material would you make a bridge out of? Brainstorm list of considerations in building a bridge.
Kinesthetic activity: The human suspension bridge. Compression vs tension
Direct instruction on stress and strain. Includes stress/strain diagrams.
Worksheet – individual work on stress and strain.
Small groups to break metal dogbones while working on worksheets.
Class discussion to introduce SEM in contrast with light microscope.
Small group activities – stations to be used for classroom management during SEM
## Calendar of Unit – Weeks 1 & 2:

<table>
<thead>
<tr>
<th>Monday</th>
<th>Tuesday</th>
<th>Wednesday</th>
<th>Thursday</th>
<th>Friday</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leading question: What will you make your bridge out of?</td>
<td>Complete materials testing</td>
<td>Introduction to the SSA 1000</td>
<td>Finish SSA 1000 testing</td>
<td>Introduce SEM</td>
</tr>
<tr>
<td>Introduction to materials testing, stress/strain diagrams.</td>
<td></td>
<td>Small groups (2 students) established to break dog bones</td>
<td>Students work on worksheets while waiting.</td>
<td>Students to prep samples</td>
</tr>
</tbody>
</table>
State Standards
High School

1. Structure and Function: A system’s characteristics, form, and function are attributed to the quantity, type, and nature of its components.

2. Interaction and Change: The components in a system can interact in dynamic ways that may result in change. In systems, changes occur with a flow of energy and/or transfer of matter.

3. Scientific Inquiry: Scientific Inquiry is the investigation of the natural world by a systematic process that includes proposing a testable question or hypothesis and developing procedures for questioning, collecting, analyzing, and interpreting multiple forms of accurate and relevant data to produce justifiable evidence-based explanations and new explorations.

4. Engineering Design: Engineering design is a process of formulating problem statements, identifying criteria and constraints, proposing and testing possible solutions, incorporating modifications based on test data, and communicating the recommendations.

Detailed:
H.1 Structure and Function: A system’s characteristics, form, and function are attributed to the quantity, type, and nature of its components.

H.2 Interaction and Change: The components in a system can interact in dynamic ways that may result in change. In systems, changes occur with a flow of energy and/or transfer of matter.

H.1P.1 Explain how atomic structure is related to the properties of elements and their position in the Periodic Table. Explain how the composition of the nucleus is related to isotopes and radioactivity.

H.1P.2 Describe how different types and strengths of bonds affect the physical and chemical properties of compounds.

H.2P.1 Explain how chemical reactions result from the making and breaking of bonds in a process that absorbs or releases energy. Explain how different factors can affect the rate of a chemical reaction.

H.2P.2 Explain how physical and chemical changes demonstrate the law of conservation of mass.

H.2P.3 Describe the interactions of energy and matter including the law of conservation of energy.

H.2P.4 Apply the laws of motion and gravitation to describe the interaction of forces acting on an object and
the resultant motion.

H.3 Scientific inquiry is the investigation of the natural world by a systematic process that includes proposing a testable question or hypothesis and developing procedures for questioning, collecting, analyzing, and interpreting multiple forms of accurate and relevant data to produce justifiable evidence-based explanations and new explorations.

H.3S.1 Based on observations and science principles, formulate a question or hypothesis that can be investigated through the collection and analysis of relevant information.

H.3S.2 Design and conduct a controlled experiment, field study, or other investigation to make systematic observations about the natural world, including the collection of sufficient and appropriate data.

H.3S.3 Analyze data and identify uncertainties. Draw a valid conclusion, explain how it is supported by the evidence, and communicate the findings of a scientific investigation.

H.3S.4 Identify examples from the history of science that illustrate modification of scientific knowledge in light of challenges to prevailing explanations.

H.3S.5 Explain how technological problems and advances create a demand for new scientific knowledge and how new knowledge enables the creation of new technologies.

H.4 Engineering design is a process of formulating problem statements, identifying criteria and constraints, proposing and testing possible solutions, incorporating modifications based on test data, and communicating the recommendations.
The big ideas in nanoscale science included in the unit Tim designed are: size and scale, structure of matter, forces and interaction, tools and instrumentation, models and simulations and science, technology and society. The following four categories of responses provides evidence of Tim’s metastrategic thinking related to his reasons for selecting these big ideas in nanoscale science and technology to include in unit that inform the research sub question, *of the nine “big ideas” in nanoscale science and technology, which are the big ideas that teachers choose to teach in their Project NANO unit and why?* and the research question, *how do teacher participants in the 2012 Project Nanoscience and Nanotechnology Outreach (NANO) program negotiate the inclusion of novel science and novel technology into the science curriculum?* The four categories are; the type of unit, engineering design cycle and group work to develop specific language and procedural skills and embedded assessments of student learning.

**Type of unit.** Tim envisioned his unit as an extension of a Project Lead the Way lesson to look more deeply at principles of engineering related to the four big ideas he used to structure his unit. These ideas include “properties of materials: the type of material will significantly affect how structurally sound it is” (size and scale; structure of matter), “technology improves our ability to characterize the properties of materials” (tools and instrumentation), “how an SEM works and how it differs from a light microscope” (tools and instrumentation), “how to use part of the engineering design process” (science, technology and society).

**Engineering design cycle.** The teacher designed a simulation wherein students pretended that each group represented a professional engineering firm preparing a bid to
build a bridge. The culmination of the unit involved the students in drawing upon what they learned about material strength to make informed choices about materials they chose to use to build and test the strength of scale model human-suspension bridges to examine the ideas of compression verses tension (models and simulations). Tim envisioned this application of knowledge and skills as a critical step in the learning process that would ensure that students would be able to integrate new knowledge of math and science and to understand how engineers use scientific research to inform their design in a manner that is distinct from scientific inquiry. He claimed that this is important because there is a strong likelihood that his students would use advanced technological tools in their future and it is important that they understand how to use tools to complete the engineering design Plan, Do, Check, Act (PDCA) cycle.

**Group work to develop language and procedural skills.** During the summer workshop and one-on-one interview, Tim expressed that he designed a guided inquiry experience for students to explore what he described as a “dry topic of stress and strain, which are rather abstract concepts that students often misconceive as being the same thing.” He drew upon his metastrategic thinking to design a unit he believed may not only improve student engagement but also provide learners with the opportunity “to avoid focusing solely on the computer to provide the answers but rather to recognize the underlying technology married with computing ability.” For each of the four big ideas that Tim built his unit around, he said in his CoRe that learning technologies made possible with the use of the SEM technology “help the student build context in understanding different materials have different physical properties and these can be
observed rather than simply inferred” using both quantitative and qualitative reasoning skills.

Tim wrote in his unit plan and described in class prior to the beginning of the first classroom observation which took place on the second day of the unit that he began the unit by explaining the background of the project prior to the arrival of the Project NANO toolkit in the classroom. He said that each mock “engineering design team” would choose to test three of five materials they felt to be the most likely candidates used to build their bridge at the end of the unit. He provided a student work packet that included instructions for each station activity and described final products that would be used for the summative assessment of the unit. Although this work packet involved some fill-in-the-blank response elements, the packet also involves interactive writing elements. Each worksheet in the packet included questions that prompted students apply math and science skills to solve problems and to connect the content of the activities to the big ideas.

Tim assigned each class of students into five small groups and designed a series of stations that the groups rotated through over the course of the two-week unit of instruction. Prior to beginning the unit, Tim said during a classroom observation that he selected a student to act as the “team leader” for each group. In preparation to serve as a team leader, he instructed these students on how to use the SEM and Leica functions and pre-taught them many of the engineering concepts that their group would explore throughout the unit. Each student team leader was instructed on methods they would use with their team to divide up the work between the members, gently challenge thinking
within the group and facilitate argumentation based on emerging evidence. The teacher met with each team leader either as a group or individually at the beginning and ending of each class to check in on each of the groups’ progress and to provide the student leader with advice as to how to manage their team in the way a professional engineering team manager would manage a team. Tim repeatedly drew upon stories from his own professional experience to provide examples of problem solving strategies both in terms of approaching the engineering testing problem and in terms of managing personalities with their team.

Because the unit involved proscribed elements in the work packet where in many cases there was only one correct answer to fill-in-the-blank, the unit can be characterized as proficient inquiry rather than exemplary inquiry. However, during the summer workshop the teacher explained his metastrategic thinking for providing structural elements intended to serve as “support for students to think on their own.” For example, the work packet contained a checklist of activities students used to track their own progress through the stations. Tim said that this approach ensured that students would keep track of their own progress throughout the unit including monitoring their use of time to ensure that they completed each station task on the list by the deadline. Another example of support the teacher embedded in the unit are lectures strategically situated at critical points within the unit.

For instance, at the beginning of the first class, Tim was observed to use the interactive white board to show photographic micrographs (photos) of three of the metals students would be examining side-by-side at 500, 1000 and 5000 times magnification and
asked students to make and record initial observations of the materials instead of lecturing on the materials. He stressed the importance of capturing images of the same material at multiple scales and then doing the same thing for the other two materials using the same scales so as to allow for an accurate cross comparison of materials at the same scales. He chose to emphasize this point based on his PCK that students often forget the importance of comparing materials at the same scale, which makes a true comparison impossible.

**Embedded assessments of student learning.** Tim said in his unit plan, CoRe and during an interview that he designed this lesson to assess prior learning, assist students in making connections to the concepts explored earlier in the year and to prepare students to discuss their observations. While at the SEM during the workshop, he spoke about how he considered how to phrase question prompts for this lesson using student friendly language to stimulate class discussions to compare how each of the materials behaved in the destruction test by using descriptive words such as “it pulls like taffy before it breaks, snaps clean off or has rough edges.”

Tim engaged the students in a whole-class discussion wherein he asked students to characterize the structure of each material and characterize the breakage they observed in each of the materials. The teacher employed formative assessment prompts to guide the discussion and calibrate students’ use of appropriate engineering terms related to the software, websites and microscopes used in the project. He modified the lessons using formative assessment questioning probes throughout each lesson to guide student thinking, challenge alternative or misconceptions and ensure that each student understood
what characteristics they would be looking for in their own samples and words used to
describe their observations.

Tim established fifteen-minute rotations on the SEM to accommodate each group
having the chance to work with the SEM at least twice during the two-week unit.
However he did not establish time limits for the other stations but instead allowed the
students to manage their own time using the check-list of stations to monitor their own
progress. Tim said during his interview that he repeatedly stressed to the class that
seniors in high school have the ability to work more independently than younger students
do and that students preparing to enter college need to take advantage of opportunities to
practice efficiently managing their time with the help of team leaders. Tim also
mentioned to the researcher following the second classroom observation that the fact that
he had small class sizes that met for a ninety-minute period, five-days per week made a
difference in terms of reducing stress that may otherwise have been caused by severely
limited time. Because there was adequate time for groups of students to complete the
tasks almost entirely in class, he said that he felt less compelled to control their use of
time more tightly.

Tim followed the strategy suggested during the summer workshop to have one
group watch the group of students on the SEM before taking their turn on the SEM. The
observation group was referred to as the “on-deck” group. Thus the terminology
suggested in the summer workshop was maintained. Similarly, the language used to
prepare the sample, load the sample, and operate the SEM controls was observed to be
consistent with the summer workshop and was rigorously maintained with each group
that used the SEM. In the fact, Tim shared during his interview that the students were insistent that the terminology be consistently used explaining to one another that they didn’t have time “mucking around by having to explain themselves with new words all the time.” For example, each class consistently used the term “fiduciary mark” to describe the cross pattern pressed into the carbon tape on the sample stub to establish four quadrants on the stub that could be notated in a worksheet. In this way students could load four separate samples onto one stub and keep track of what sample was in each quadrant when they viewed the sample with the SEM.

Tim also drew upon ideas from the summer workshop to facilitate students as they learned how to operate the SEM. First he modeled the sample load procedure and demonstrated how each of the controls work for various functions to raster the image, auto and manual focus, fine focus, contrast, capture an image, measure features of a sample and eject the sample cup. He was observed introducing specific terminology meant to guide the students through the load protocol explaining that they would use the same terms to verbally express the steps to their group when it was their turn. He explained to each group of students that this is a way to check that each person understands the steps and performs them correctly.

As each person approached using the SEM for the first time, the teacher asked each student to recite the list of materials that can and cannot be put into an SEM and to verbally describe their steps to model to the rest of the group on the on-deck group what he wanted each person to do when it was their turn to prepare and load samples and operate the controls on the SEM as the move from the optical view to the SEM mode.
Once they were in the SEM mode, students were expected to utilize terms used during the whole group discussion at the beginning of class to describe characteristics of the material and the point of breakage. After modeling one time, rather than repeating these terms, Tim asked students to discuss what they observed and then respond to students’ questions to guide their choices of words used to describe various features of the material.

During the summer workshop, the co-instructors emphasized that once the samples are in the SEM, the image has been rastered and the instrument is switched to the SEM mode from the optical mode, there is very little that students can do to damage the instrument. Thus, after modeling how to use the instrument and conducting the formative assessment to ensure that students knew how to operate the instrument and then describe the images using the correct scientific and engineering terminology, Tim said during a classroom observation that he felt free to move to the Leica microscope that was set up about five feet away from the SEM to check to make sure that the students knew what to do at that station. During the second group rotation on the SEM, the researcher noticed that the instructor stayed with each group during the sample preparation and load sequence but then moved around to the Leica and then to the other stations to support the students around the room. Thus, he was able to facilitate a guided inquiry experience throughout the unit using strategies such as questioning probes rather than direct instruction and occasionally advising the team leaders with brief tips related to content, process and group management.
Tim described his metastrategic thinking to the researcher by saying that his ability to move about the room made the difference between making this a less-effective discovery inquiry experience verses a guided inquiry experience that he prefers. He drew upon his PCK to inform this decision saying that in his experience, gentle guidance is more successful with students then “free-for-all exploration”.

**Tim’s Content Representations (CoRe)**

As mentioned above, due to the fact that Tim was the only engineering design and physics teacher in the summer workshop session he attended, he created the following CoRe table on his own. He approach the development of his CoRe in an iterative process beginning with drafting his learning objectives on the CoRe, engaging in scientific inquiry to inform his thinking, and then recording his ideas on his unit planning template and rationale for his ideas in his CoRe table. Each morning he met with one of the workshop instructors to share his writings on his CoRe and unit plan and then adjusted and built upon his prior knowledge to develop and organize his unit. Tim presented the following CoRe table (Table A.5) on the last day of the workshop,
### Table A.5

**Tim's Content Representations (CoRe)**

<table>
<thead>
<tr>
<th>This CoRe is designed for Principles of Engineering (PLTW) - 11th and 12th grade</th>
<th>Researcher memos &amp; codes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Big Ideas</td>
<td>A) Properties of materials: the type of material will significantly affect how structurally sound it is.</td>
</tr>
<tr>
<td></td>
<td>B) Technology improves our ability to characterize the properties of materials.</td>
</tr>
<tr>
<td></td>
<td>C) How an SEM works and how it differs from a light microscope.</td>
</tr>
<tr>
<td></td>
<td>D) How to use part of the engineering design process</td>
</tr>
<tr>
<td>What you intend the students to learn about this idea.</td>
<td>Understand stress, strain, tension, compression, and shear.</td>
</tr>
<tr>
<td></td>
<td>Contrast building a footbridge with trial and error methods to engineering design of a bridge carrying thousands of people and tons of supplies.</td>
</tr>
<tr>
<td></td>
<td>The basic mechanics of a SEM.</td>
</tr>
<tr>
<td></td>
<td>How microscopes work</td>
</tr>
<tr>
<td></td>
<td>How to use SEM</td>
</tr>
<tr>
<td></td>
<td>Stress and strain</td>
</tr>
<tr>
<td></td>
<td>Compare, contrast</td>
</tr>
<tr>
<td></td>
<td>Mock engineering design project</td>
</tr>
<tr>
<td>Why is it important for the students to know this?</td>
<td>In order to have context to evaluate, compare and contrast different materials.</td>
</tr>
<tr>
<td></td>
<td>Strong likelihood they will be using technologically advanced tools in their future.</td>
</tr>
<tr>
<td></td>
<td>Strong likelihood they will be using technologically advanced tools in their future.</td>
</tr>
<tr>
<td></td>
<td>This is a key component of my class. Engineering methodology is distinct from scientific inquiry.</td>
</tr>
<tr>
<td></td>
<td>Skills building</td>
</tr>
<tr>
<td></td>
<td>Evaluate, compare and contrast</td>
</tr>
<tr>
<td></td>
<td>ED distinct from SI</td>
</tr>
<tr>
<td>What else do you know about this idea (that you do not intend the students to know yet?)</td>
<td>Shear forces are related to stress and strain. We will focus on tensile/compression strength.</td>
</tr>
<tr>
<td></td>
<td>I intend to stress the concept. The number of examples that we discuss will be limited in scope.</td>
</tr>
<tr>
<td></td>
<td>Details of the electron source. How this SEM differs from larger, more advanced SEM/TEM.</td>
</tr>
<tr>
<td></td>
<td>Engineering design can be summarized as PDCA (Plan, Do, Check, Act). I will focus on “Plan”. They will be familiar with the subsequent steps of the process.</td>
</tr>
<tr>
<td></td>
<td>Tensile strength and compression strength</td>
</tr>
<tr>
<td></td>
<td>PDCA cycle</td>
</tr>
<tr>
<td>Difficulties/limitations connected with</td>
<td>Stress and strain have specific meanings that are different from</td>
</tr>
<tr>
<td></td>
<td>It could be a dry lecture if not approached in an engaging/inquiry</td>
</tr>
<tr>
<td></td>
<td>Reinforcing a concept that is unique and distinct from science</td>
</tr>
<tr>
<td></td>
<td>Abstract concepts</td>
</tr>
<tr>
<td><strong>teaching this idea:</strong></td>
<td>common use. Stress and strain are abstract concepts. manner. inquiry.</td>
</tr>
<tr>
<td>------------------------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td><strong>Common misconceptions students hold about this idea:</strong></td>
<td>Stress and strain are the same thing. Focusing on the computer as the answer rather than recognizing the underlying technology married with computing ability.</td>
</tr>
<tr>
<td><strong>Difficulties/limitations connected with use of scientific instruments</strong></td>
<td>All equipment in this unit will be limited in number and be complex in its operation (SEM, Stress/Strain Analyzer, light microscope)</td>
</tr>
<tr>
<td><strong>What are some learning opportunities that are made possible with the use of the SEM technology</strong></td>
<td>Help the student build context in understanding different materials have different physical properties and these can be observed rather than simply inferred. Help the student build context in understanding different materials have different physical properties and these can be observed rather than simply inferred.</td>
</tr>
<tr>
<td><strong>Knowledge about students’ thinking which influences your teaching of this idea</strong></td>
<td>A general understanding of metals and alloys including some basic chemistry. Technologically savvy students. Familiar with operation of light microscope. Technologically savvy students.</td>
</tr>
<tr>
<td><strong>Knowledge about</strong></td>
<td>Connection with their physical understanding of</td>
</tr>
<tr>
<td>students' thinking that influences how you integrate technology into the lesson</td>
<td>world. Bridges are a simple but effective way to relate to material strength.</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Other factors that influence your teaching of this idea.</td>
<td>Start with leading question. Allow students to build personal connection to the topic. Some direct instruction required initially in order to build knowledge. Inquiry activities incorporated in order to allow students to build their personal knowledge</td>
</tr>
<tr>
<td>Teaching procedures (and particular reason for using these to engage with this idea).</td>
<td>Final assessment allows the student to construct their conclusion as to how the nano-scale structure of metals relates to the macro-scale strength properties.</td>
</tr>
<tr>
<td>Specific ways of ascertaining student's understanding or confusion around this idea (include likely range of responses.)</td>
<td>Evaluation of student example and explanation of how technology improved another area of scientific investigation.</td>
</tr>
</tbody>
</table>

*CoRE template modified from a template created by Loughran, Berry and Mulhall (2006).*
Classroom Observations. Three observations were conducted in each of Tim’s two engineering classes. For each of the observation visits, I observed the morning engineering class, ate lunch with the teacher so that we could discuss his metasategic thinking and PCK used in the lesson and then I observed the engineering class immediately after lunch. Once again, the EQUIP instrument was used for each of the observations. The following information further informs the research question, how do teacher participants in the 2012 Project Nanoscience and Nanotechnology Outreach (NANO) program negotiate the inclusion of novel science and novel technology into the science curriculum?

The overall EQUIP score for three observations is three, proficient inquiry. Interestingly, there was not a significant difference between the scores for the morning and the afternoon classes. The following section will summarize the EQUIP scores for each of the observations.

The first pair of observations took place on the day that the teacher introduced the extension unit. Tim’s brief presentation at the beginning of the class clearly established the learning objectives, described the activities at each station and made explicit connections between the content involved in each activity and the big ideas. Throughout the lesson, the teacher posed guiding questions that encouraged synthesis of new knowledge with the content in the previous units on materials. He was observed to repeatedly modify his instruction as he modeled the activities at the stations in response to student’s questions or incorrect statement. Rather than directly correcting misconceptions, Tim asked either the student or whole group of students questions to
challenge misconceptions. The main reason that the lesson scored a three as a proficient inquiry rather than 4 as an exemplary inquiry is that many of the student worksheets had fill-in-the-blank style prompts rather than interactive science journal style prompts or another sort of approach used to elicit higher order thinking rather than recitation style responses. Thus, students had only minor input on how to record and organize data.

The second pair of observations each scored three of four points, which is at the level of proficient inquiry. The process-focused activity required students to use higher order thinking skills to interpret data and students’ questions consistently guided classroom discourse. When the teacher did interact with the groups beyond providing technical guidance on the instruments, he did so by keying into group discussions and asking questions rather than intervening with direct instruction. The majority of the teacher’s questions were intended to guide students towards connecting the concepts addressed in the station activities with the big ideas related to stress and strain. However, at several intervals throughout the observations, approximately one-third of the students in both the afternoon and morning groups tended to disengage from the activity as soon as the teacher turned to work with another group. In each group, the student team leaders remained consistently on task throughout each observation. Students who went off task occasionally checked back in with their group leaders, established that the leaders were continuing to complete the tasks for the group and with that, disengaged again. For this reason, the overall score for the first pair of observations is a three, meaning the lesson scored as a proficient inquiry rather than exemplary inquiry.
The third and final pair of observations each scored a four, an exemplary level of inquiry. In recognition of the fact that several students appeared to be disengaged earlier in the unit, the teacher had met with the group leaders and established discrete “jobs” for students to do to complete the final report. Team leaders then presented these jobs to their group and students self-selected a group of jobs to take responsibility for completing and sharing with the rest of the group to check their work such as mathematical calculations and graphical representations of data. The level of student engagement and higher order thinking for the previously disengaged students increased significantly at this point. Again, the teacher acted as a facilitator and allowed students’ questions to guide his involvement. The lesson seamlessly integrated activities that involved application of skills and knowledge, argumentation based on evidence including error analysis.

**Tim’s Knowledge, Skills, Experiences, Community and Assessment Scoring Guide scores.** As reported in the following table, Tim’s unit scored very well in nearly each curriculum element listed on the Evaluation Criteria for Science Inquiry/Engineering Design Curriculum Unit scoring guide.
Table A.6

**Cumulative Scores for each Curriculum Element in Tim's Unit**

<table>
<thead>
<tr>
<th></th>
<th>Knowledge and Concepts</th>
<th>Science Inquiry Skills</th>
<th>Student Experiences</th>
<th>Learning Community</th>
<th>Assessment of Student Achievement</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Possible Points</strong></td>
<td>12</td>
<td>15</td>
<td>12</td>
<td>12</td>
<td>15</td>
<td>66</td>
</tr>
<tr>
<td><strong>Tim’s Score</strong></td>
<td>12</td>
<td>14</td>
<td>11</td>
<td>10</td>
<td>14</td>
<td>61</td>
</tr>
</tbody>
</table>

Tim reported in his CoRe and said during the workshop that he specifically used the scoring guide to ensure that he considered and communicated his thinking on each component of the unit design. Because Tim’s unit did score so well in nearly every category, it is most useful to describe the few categories that the unit did not score the full amount of points possible rather than providing an exhaustive description of why he scored the full points on each category.

Tim’s unit scored all of the total points possible for the Engineering Design Skills element except for the category; *Students identify variables and develop inquiry design(s) and data collection protocol(s)*. The reason that that unit scored only two of three points for this criteria is that he provided the variables that the students explored rather than allowing the students to generate a fully open-ended inquiry design and he dictated most of the data collection protocols by listing them in the student work packet and repeatedly describing these to the team leaders and to the entire class. However, he did allow some
degree of freedom to students when he allowed them to choose to examine and compare three out of the five possible materials listed in the packet. Students made their decisions as to what materials they would examine with the microscopes after manually annotating the stress and strain curves for each of the materials and deciding which materials they were more likely to select to build their model bridges with at the end of the unit.

For the Student Experiences curriculum element, Tim’s unit scored three of three possible points for each of the categories except for the Accommodates student diversity in strategies, approaches, abilities, cultural perspectives and learning styles. Although Tim did address accommodations for learning levels and styles by listing ideas such as preparing team leaders to assist so-called weaker members of the team and providing visual, audio and kinesthetic learning experiences to explore the big ideas in the unit, when asked about the lack of mention about differentiation for culturally diverse students the teacher replied that the school he works with is a very culturally homogenous group of students and that the main strategy he used to accommodate for diversity was to carefully define terminology and procedures that would be used consistently throughout the unit.

To ensure that each student correctly understood and consistently used specific engineering design terms such as sheer and strain and technical terms relate to the instruments, the instructor embedded both informal formative assessment probes throughout the unit and formal assessment in the final engineering design and failure analysis students presented in the completed work packet, report and presentation. These formative and summative assessment strategies also fulfilled all of the categories in the
scoring guide listed under Learning Community and Assessment of Student Achievement.

For the Learning Community section, the unit scored three of three points in each of the categories with the exception of the last category; *Students communicate and defend the results of their inquiry to their instructor and peers.* The unit scored two of three points because although students did communicate evidence and defend results while at the SEM and in the written work packet and report, the researcher did not observe the students actually defending their ideas during the final group discussions with their peers. Rather, each of the five groups in each class simply presented their data, answered questions posed by the teacher to clarify ideas and did not argue to defend their data before their instructor and peers.

In the case of the last curriculum element, *Assessment of Student Achievement*, the units scored three of three possible points in every category except for, *Assessments provide multiple chances and formative options to revise thinking.* Although the teacher did frequently probe students using questions that prompted students to assess their own thinking and revise their ideas, there were no formal mechanisms put into place that would allow students multiple chances and formative options to revise their thinking. The only items that students submitted for a grade were the work packet and report submitted at the end of the unit and there was no mention made that students would have a chance to revise their thinking found in either of these documents.

**Tim’s Pre and Post Survey scores.** Tim participated in the third section of the summer workshop, which meant that he took the version of the pre and post survey that
included two multiple choice questions in addition to the four open-ended response questions, one of which was only slightly reworded following the first session of the summer workshop. These two multiple choice questions are:

1. Circle the unit of measurement used to measure the head of a pin (answer: millimeters).
2. Which of the following cannot be loaded into an SEM? (answers, magnetic metal, wet material, live organisms).

The following table A.7 presents Tim’s pre and post survey scores:

**Table A.7**

**Tim’s Pre and Post Survey Scores**

<table>
<thead>
<tr>
<th>Pre – Post Survey Questions</th>
<th>Pre Survey</th>
<th>Post Survey</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circle the unit of measurement used to measure the head of a pin (Answer: millimeters).</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Which of the following cannot be loaded into an SEM? (Answers: magnetic metal, wet material &amp; live organisms).</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>What is the difference between an optical microscope and an SEM”</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Describe 5 key components of the scanning electron microscope (the mechanics of the tool)</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Describe safety protocols related to working with secondary level students and a table top SEM</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Provide a brief description of how you might integrate optical and electron microscopes in a course to instruction students on form and function related to the discipline you teach.</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>
Tim missed one point on the entire pre and post survey. On the second multiple choice question he failed to circle *magnetic metal*, although when asked about this omission after taking the pre survey, Tim said that he actually knew that magnetic metal could not be placed in an SEM based on his prior professional experience working with SEMs as an engineer and that this was simply an oversight on his part. He was able to accurately describe the magnetic metals would fly up into the SEM and get stuck on the detector, thus either breaking the SEM or reducing the detection area. Because he was able to accurately describe this limitation of the SEM on the first day of the workshop before the workshop presentation on the limitations of the instrument, he proved that his failure to circle magnetic metal was indeed an oversight. With this consideration in mind, a ceiling effect was observed in that the survey instrument itself was not challenging enough for a teacher who had many years of professional experience working with nanoscale concepts and technology. Therefore, in Tim's case, this survey instrument is not useful for investigating sub-questions one and three which relate to changes in the teacher’s metastrategic thinking and PCK and evidence of content knowledge gains.

In contrast, the pre and post survey, the classroom observations, interview data and CoRe call-out reflections did result in the development of a rich description of how this teacher thought about organizing the introduction of nanoscale science and the SEM into the engineering curriculum. The following section presents the categories of PCK developed from Tim’s Content Representation (CoRe) table, call-out reflections and one-
on-one, one-hour interview following his full evaluation the student learning outcomes for the two engineering design classes he taught the unit in.

**Evidence of changes in Tim’s thinking found in the CoRe, call-outs and interview.**

The following description of Tim’s metastrategic thinking and PCK inform the research question, *how do teacher participants in the 2012 Project Nanoscience and Nanotechnology Outreach (NANO) program negotiate the inclusion of novel science and novel technology into the science curriculum? and how, if at all, do teachers’ metastrategic thinking and PCK change between the summer workshop and the reflection period following the implementation of the Project NANO unit?*

The following categories of PCK were developed from the CoRe, call-out reflections and one-hour, one-on-one interview. The five categories and two sub-categories are:

- Sequencing the unit as a Project Lead the Way extension unit
- Time management
- Technical Pedagogical Content Knowledge
- Unit extensions
- Student assessment

**Sequencing the unit as a Project Lead the Way extension unit.** During the summer workshop Tim chose to rearrange the sequence of Project Lead the Way curriculum to accommodate the integration of a nanoscale project, “I scheduled the SEM for late January thinking that I could add in a stress and strain unit to the Project Lead the Way curriculum before the tress building and testing unit. This is partly because of when
I could schedule the Phenom and partly because it’s the most logical fit for integrating nanoscale and the SEM. Especially since this is the first time I’ve used an SEM to teach with Project Lead the Way, so I’m figuring things out this year.”

He went on to further describe his metastrategic thinking during his interview, “I gave way more time to the topic than Project Lead the Way does, probably twice or three times as much time. See the way Project Lead the Way is written, students build tresses and then learn about the effects of various forces on the structures through a series of tests. Then they learn about stress and strain, which is a logical order for the unit. The way I did it put understanding stress and strain [conceptually] first and then virtually building a bridge and testing it using a computer program to look at the effects of various different types of forces.”

Tim was concerned that adding the complex concept of tensile strength to the Project NANO unit would confuse students, so he said during his interview that he decided that the material strengths unit would be good preparation for understanding concepts related to tensile strength in the Project Lead the Way Unit to follow. He learned throughout the implementation of unit in the past that students were attempting to integrate their understanding of each of the materials by considering concepts that closely relate to tensile strength.

Tim said during his interview that he realized that students held misconceptions related to the types of stress likely to cause bridge failure and misconceptions about the term “failure” itself in terms of understanding engineering theory on brittle and ductile failure from the perspective of both microscopic and macroscopic material failure. His
PCK expanded as he recognized a common confusion students had about the difference between the physics concepts of stress and strain. Based on this observation, his metastrategic thinking informed his choice for how to adjust the unit and scaffold information to ensure that students are better prepared in the future to understand and apply Hooke’s law, or modulus of elasticity, to interpret the characteristics of the materials and how they deform and then break when pulled apart.

With the assistance of his Project NANO coach, Tim said during his interview and in his call-outs that he also considered the sequencing of his own learning and incremental changes he is ready to make now that he has taught the unit one time.

During his interview Tim related:

The Project NANO coach and workshop instructors definitely influenced how I designed the unit. They got me started, they gave an outline of how to think about organizing the class with stations, sample lesson plans and taught us how to use the Phenom and Leica with students. My Project NANO coach teaches down the hall in the same building, so we had lots of informal conversations about how it was going and ideas for what to change, and problem solving technical issues with the Phenom and Leica. We are also talking now about ideas for what I’m going to work on this summer to change my unit.

For example, Tim related during his interview, “I’m ready, as a learner myself, to investigate more about different types of SEMs and what they can do so that I can add that information to the unit next time. I also want to know about different types of electron microscopes and add that in for next year. So that will be part of that frontloading I’ve talked about next time that I wasn’t ready to do this year.”

**Time management.** Tim discussed during his interview that he is also reconsidering how to sequence the unit in terms of time management:
Now that I taught this one time, I see that I can actually frontload the unit a bit better… I learned something about time management and how we allocated time. For example, we should have prepped the samples before the Phenom came to my room. We lost two and half days when the SEM was in the room just preparing samples. So starting the unit a little earlier so that we can do the stress and strain analysis lesson, build some background knowledge about the concepts involved in the project and then prepare samples before the Phenom [SEM] arrives.

**Technical PCK.** Another way that Tim built upon his PCK is that he negotiated technical problems with one of the Project NANO instruments. In this case, the problem was with the Leica microscope rather than the SEM. Students consistently had trouble capturing a focused image with the Leica and storing images on the secure digital (SD) card. Tim said in his call-outs and in his interview that many students reported that they resorted to capturing images using their Smart Phone camera since they couldn’t get the Leica image capture function to work properly. Students also reported problems with the SD card in that it filled up very quickly and required repeated transfers of images to a computer, which wasted valuable time at the microscope station. Tim expressed concern that students were unable to use the $1,000 high quality microscope lens and were using cameras on their phones that produced much lower quality images.

Tim shared in his interview that next year he will use a fire wire to connect the Leica to a laptop computer so that every student in each group may see the image at the same time and discuss the characteristics of each material and problem solve focusing on views under the microscope that best demonstrate the points they want to make about the structure of the materials and how each of the materials break. Tim says that he thinks that this solution will help to students to avoid problems with focusing, capturing and saving images.
Tim also expressed that the example template provided through the summer workshop meant to guide students through the use of the Leica controls was actually written for a different microscope and didn’t work for the Leica model provided through Project NANO. He said that next year he will rewrite the instructions to fit the correct model and also step the students through the use of the Leica microscope in the same way he did with the SEM rather than expecting students to figure it out on their own using written instructions.

**Adding options for extensions.** Tim also reports during the interview and in his call-outs that he now feels ready to add extensions to the unit:

Science fair would be a good fit for this project; we actually do have one student who is developing an idea for what he wants to do for a science fair engineering project next year. Next year I want to encourage more students to come in after school or during lunch to just check out their samples, to just look at whatever they are curious about and want to examine to see what the SEM can do and just to explore a bit. Only one student did that this year, and actually she came in pretty much every chance she got. There are discussions around here [his school and the feeder middle school] that we should do more to set up opportunities for kids to just explore and have fun, you know in addition to the more structured classroom experiences in science and engineering classes. Some of those may turn into science fair projects; some may just be for the sake of pure exploration, which is important too.

**Student assessment.** The next change in Tim’s thinking related to PCK had to do with student assessment of learning. Tim reported during his interview that the primary means of assessment in the unit was summative in nature:

The main assessments were the final reports. Most of the groups did great, I saw that they learned what I was wanting them to learn; they were making the connections. I was disappointed about a couple of the groups who didn’t seem to make the right connections, they just didn’t get it. And since the report was summative assessment, at the end, I didn’t know until after the unit was over that they weren’t getting it… partly because I was stuck at the SEM and partly because I didn’t have whole group discussions where I would have been able to
see where they were. I think that those whole group discussions would have helped the kids to figure out for themselves that they were off-track. They could have asked questions to help them figure out the next steps and they could have either worked with another group or asked me for help when they needed it. So that’s something I’ll change next year, I’ll make sure that we come together on a regular basis to talk about their metaphors for what they think is going on with the metals, use the engineering terms to make sure everyone really gets the meaning of that vocabulary and talk about evidence and how we are thinking about it.

Tim stressed during his interview that the student’s final reports support something he know about the student thinking that informs how he decided to assign students to groups, “it’s not always the brightest kids who make the most important contributions to the team. The smartest students don’t always make the connections. Sometimes it’s the really creative thinkers, who aren’t necessarily the smartest kids, who come up with really interesting ways to look at a problem from multiple angles. It’s that non-linear thinking that can be so important to figuring out a problem.” Thus he wasn’t surprised at all that each of the final group reports were different. In fact, he said that he would have been more disappointed if the reports did all look the same as he expects variation among groups.

Tim described his PCK for how he plans for variation in the classroom through two main means; providing activities that offer a variety learning modalities including kinesthetic, visual and audio-based learning experiences and the use of formative assessments to inform differentiation in the classroom. During the interview Tim shared the following reflection:

I think I did a pretty good job this year at considering different styles of learning and levels of learning. Kids did hands-on testing with the stress and strain analyzer and the microscopes and then used software at the end to build a model bridge with the materials they tested and selected based on what they learned in
the lectures and from their own observations. So there was a variety of activities to appeal to different kinds of learners.

He also describes his PCK for how he designed the station rotations and new ideas developed through this first experience:

The unit included some stations that worked out really well and built on each other in terms of complexity as students moved from station to station. Some of the stations turned out to be distracting and didn’t really build in complexity the way I wanted. So at the follow-up this summer, I’ll take out things like the nanoscale crossword puzzle and find something that gets students thinking and talking more, you know so they aren’t just solving puzzles or equations on their own, but really thinking about how to make comparisons. I want them to have more higher-order thinking discussions.

Throughout the classroom observations, once the samples were safely loaded and students had begun navigating in the SEM mode, the teacher knew the instrument would be safe if he circulated around the groups. As he circulated, he used formative assessment prompts to guide students in the group by asking students to report on their progress, asking content-based probing questions, suggesting possibilities to consider, correcting mathematical and other thinking errors and noting ideas for how to prompt group managers after class, “I met with project managers periodically to prepare them for the next step in the unit, give them some direction on how to work with their group and check to see how it was going in the group.” Again, adding group discussions to frequent check-ins with group managers is an additional formative assessment strategy that he felt will enhance his own sense of what members of each group are thinking and in turn, better inform what he says to the group managers to support their groups and how he approaches individuals within the groups.

**Summary of How These Evidence Inform the Research Question**
Tim’s case is significant for two reasons. First, Tim provides an example of how a teacher with experience working with nanoscale concepts and technology thinks about integrating novel content and technology into the engineering curriculum. Working with the Project Lead the Way curriculum, he identified the SEM as a tool useful to strengthen the depth of students conceptual knowledge of stress and strain, address common misconceptions related to stress and strain and enliven a topic he knew to be dry to many students. Thus, Tim’s case provides baseline data on the entry point that a teacher with prior nanoscale science and technology experience has on a learning progression while planning, implementing and reflecting upon a nanoscale science, engineering design unit of instruction for the first time.

Secondly, Tim’s case stands as an important contribution to support the implementation of new science content standards given the fact that there are currently precious few K-12 examples available to assist teachers’ thinking as they integrate and not simply add-on nanoscale science and engineering educational experiences as required by the Next Generation Science Standards. Given that Project Lead the Way is a widely used curriculum throughout the U.S., this example could be particularly relevant and useful for professional development leaders, curriculum designers and teachers to draw upon as they negotiate the implementation of the Next Generation Science Standards into secondary education.
APPENDIX C

CASE-BY-CASE STUDY OF FOUR TEACHER PARTICIPANTS: ANNIE
Annie

Annie (pseudonym) is a veteran teacher with fifteen years of experience teaching middle-level science in a public suburban K-8 school. According to her responses on the pre-survey, she has taken six college level science courses, including graduate level science education courses, although none that included nanoscale science and technology.

In the interest of full disclosure, Annie’s graduate experiences took place over the past five years through science teacher professional development programs that I coordinated. The first was a science teacher-as-researcher program involving a graduate level Methods of Science Education research course, research coaching support and two summer symposia to support and share teacher participants’ action research. The second program involved a science content course designed to support the development of science inquiry teaching skills and six months of coaching support to implement a unit of instruction developed through the course.

Annie’s Unit of Instruction

Annie collaborated with another middle-level, in-service teacher and a pre-service teacher to develop a two-week unit of instruction focused on characterizing and categorizing biological adaptations of animal feathers, fur and scales. Annie wrote in her pre survey that she entered the course with no prior exposure to nanoscale science and technology. She said during the workshop that she did not have time to complete the pre-requisite readings or watch the videos sent in advance by the co-instructors in preparation for the workshop. Annie said that she entered into the workshop without any preconceptions as to how she might integrate nanoscale science into her curriculum. She
emphasized that she joined the program precisely because she realized that she really had
“no clue” how to approach the inclusion of nanoscale science and technology into the
eighth curriculum largely because she didn’t know any nanoscale concept prior to the
workshop.

On the first day of the workshop, teachers went around the circle and described
their preliminary ideas for what samples they would like to examine with the SEM, what
topics they would like to address and how these ideas may potentially fit into their
discipline. Annie shared during her interview that because she was unsure as to how to
approach the challenge of choosing a topic to frame her unit around, she gravitated
towards collaborating with an eighth grade science teacher because she thought that his
idea of examining fur, feathers and scales in a comparative unit would support the
development of her student’s understanding of size and scale, a foundational scientific
concept.

Following the workshop, Annie said prior to the start of a classroom observation
that she revised the unit of instruction she had created with her group to fit within her
school districts’ newly adopted science curriculum. Since she had piloted the newly
adopted middle school science curriculum over the past two years, she had recently spent
a great deal of time thinking about and discussing the strengths and limitations of the
curriculum and how to design or choose supplemental lessons to support the development
and use of students’ higher order thinking skills. Thus she was able to draw upon this
metastrategic thinking to inform her choice from her pedagogical repertoire to refine the
unit.
Annie created one unit plan that she taught in each of her science classes to develop students’ science inquiry laboratory and qualitative reasoning skills. Rather than completing the unit of instruction planning template, Annie chose to use her own, more familiar template to plan her unit. Here is Annie’s unit of instruction:
Project NANO:  
Feather, Fur, Hair, and Scales

Just How Different Are They?
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</table>
Timeline

(Assuming 45 minute class periods)

**Day 1**
Introduce SEM
- Show examples of images taken and have students make hypotheses.
- Talk about safety and equipment treatment.
- Demonstrate how to view sample.

Stub Introduction
- Demonstrate stub preparation
- Discuss what things can be viewed (limitations)

Assign Lab Groups and sign up for specimen comparisons.
- Homework: All students collect both specimens (except scales – only one student)

**Day #2**
Stub preparation
- Review stub preparation procedure
- All groups prepare one stub with both specimens.
- Explain expectations of PowerPoint and station work
- Homework: Read “Microscopes – Helping Scientists Explore Hidden Worlds” and answer questions.

**Days #3 – 5**
Station work and using the SEM
- Students will be working to complete tasks at stations and teacher will “pull” lab groups to obtain images on SEM at 15 intervals.

**Day #6**
Students work on presentation with groups.

**Day #7**
15 minutes to finish presentation and start presentations.

**Day #8 / 9**
Presentations, class discussion, and reflection
Feather, Fur, and Fish Scales

Your Task: You will be investigating the differences and similarities in the structure and function of feathers, fur, hair, and scales on a macro and micro scale.

Introduction: Organisms vary greatly based upon a number of factors some of which are easy to see and others which are more difficult. From this vast pool of variations, natural selection puts into order a combination of genes and allows the organism to adapt to their specific environment. In this lab we are going to look at the structure of feather, fur, hair, and scales at varying degrees of magnification. We will also be examining the function of feather, fur, hair, and scales to examine the connection between adaptations and evolution. The highlight of this lab is your chance to view a couple of specimens under a scanning electron microscope. This piece of equipment not only has incredible magnification capabilities, but also an incredible price tag. You are going to get the opportunity to use a piece of scientific equipment that most scientists only dream of getting to use.

ODE Standards

Structure & Function
- 8.1L.1 Explain anatomical characteristics are used to classify organisms and infer evolutionary relationships.

Interaction & Change
- H.2L.5 Explain how multiple lines of scientific evidence support biological evolution.

Scientific Inquiry
- 8.3S.2 Organize, display, and analyze relevant data, construct an evidence-based explanation of the results of a scientific investigation, and communicate the conclusions including possible sources of error. Suggest new investigations based on analysis of results.
- 8.3S.3 Explain how scientific explanations and theories evolve as new information becomes available.
- H.3S.3 Analyze data and identify uncertainties. Draw a valid conclusion, explain how it is supported by the evidence, and communicate the findings of a scientific investigation.
Student Objectives

By the end of this unit, you will be able to …

• Compare and contrast different hair, fur, feather, and scales.

• Explain the function of hair, fur, feather, and scales.

• Describe the evolutionary relationship between hair, fur, feather, and scales.

• Use the SEM, dissecting scopes, and hand lenses to make quantitative and qualitative observations.

• Explain how technology, such as the SEM, can change scientific explanations and theories.

• Identify sources of error using different types of equipment.

• Present findings to class.

LESSON OBJECTIVES

Complete the tasks below in order to collect background research and data for your final project.

1. **Background Research**
   a. Read and answer questions for the following selections: Scales, Feathers, Fur, and Hair

2. **Observe and Sketch Your Specimens**
   a. Naked eye: Draw, measure and label what you see
   b. Hand lens: Draw, measure and label what you see

3. **Dissecting Microscope**
   a. Draw and label what you see at 2x, 4x, and 8x
4. **Learn How the SEM Works**  
   a. Watch video and complete questions

5. **Purpose and Function of Fur, Hair, and Feathers**  
   a. Mini-lab – How do fur, hair, and feathers help an organism regulate their body temperature?

6. **Power of Ten Puzzle**  
   a. For this task, you should put the images in order of magnification and identify observation tool

7. **Virtual Electron Microscope**  
   a. For this task you should go the Virtual Electron Microscope Webpage and  
   b. Identify SEM images

8. **Scanning Electron Microscope**  
   a. For this task you should capture at least 3 images of each specimen under different magnifications determined during class discussion  
   b. Insert your Thumb-Drive  
   c. Image Capture       
      i. Label images before taking a picture  
      ii. Check Archive to make sure you have captured all the images you thought you have

9. **Presentation Planning (Part 1)**  
   a. Plan your presentation slides  
   b. Start formatting

10. **Presentation Planning (Part 2)**  
   a. Add images and information to PowerPoint

11. **Image J – Extension if time**
## Presentation Scoring Guide

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<tr>
<th>Student Objectives</th>
<th>Background Information</th>
<th>Collect Data</th>
<th>Data Analysis and Conclusions</th>
<th>Present findings to class</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Highly Proficient</strong>&lt;br&gt;All statements apply</td>
<td>Students include information about the composition of each specimen.</td>
<td>Students collect images that are clear and easy to identify. Images are easy to compare. All images are labeled with appropriate labels, scale bars, magnification, and tool specification.</td>
<td>Students compare and contrast the different specimens at multiple magnitudes. Students use data to make a claim. All claims relate back scientific knowledge.</td>
<td>Students included all required information. Students prepared a clear and concise presentation of their findings. Student discussed error analysis including: • Image interpretation • Issues with different tools Every student in the group participates in the presentation.</td>
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<td><strong>Proficient</strong>&lt;br&gt;Only minor omissions</td>
<td>Students include information about the purpose and function of each specimen.</td>
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<tr>
<td><strong>Nearly Proficient</strong>&lt;br&gt;1 major omission</td>
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<tr>
<td><strong>Working Towards Proficiency</strong>&lt;br&gt;2+ major omissions</td>
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<tr>
<td><strong>No evidence Missing</strong></td>
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Station #1: Background Research

When we start to look at most species in the animal kingdom they either have scales, feathers, fur, or hair. We want to examine each of these adaptations in a little more detail and understand some basic terminology associated with these adaptations.

Read each card and answer the questions below.

1. What substance makes up scales, fur, feathers, and hair?

2. What purpose do all fur, feathers, hair, and scales have in common?

3. Why are down feathers more similar to fur and hair than flight feathers?

4. Explain how and why a bird “preens”.

5. What is the main purpose of the great variation in colors associated with fur, feathers, hair, and scales?

6. If you had to hypothesize the order in which feathers, scales, fur/hair evolved, list them in order from the earliest to latest evolutionary speaking.
Station #2: Observing Your Specimen at Different Magnifications

At this station you will be first observing and drawing your two specimens using just your naked eye and then a hand lens. Be care with detail and neatness. Label all appropriate structures and complete the chart below.

<table>
<thead>
<tr>
<th>NAME OF SPECIMEN: Naked Eye Observation</th>
<th>NAME OF SPECIMEN: Naked Eye Observation</th>
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<table>
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<tr>
<th>Hand Lens Observation</th>
<th>Hand Lens Observation</th>
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<table>
<thead>
<tr>
<th>Length of specimen with naked eye:</th>
<th>Length of specimen with naked eye:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qualitative Observation (at least 3)</td>
<td>Qualitative Observations (at least 3)</td>
</tr>
</tbody>
</table>
Station #3:
The Dissecting Microscope

At this station you will examine the surface of your two samples in order to explore them at more detail.

Directions:
1. Place one sample under the microscope.

2. Focus the microscope so that your sample takes up most of your field of view.

3. Draw in detail what you see in the space provided below. Color your picture and include the magnification! If you have a cell phone with a camera, try to snap a picture of each specimen. It helps to start far away and then bring the camera closer keeping your eyepiece within your camera’s field of view.

Draw your other specimen at the same magnification.
Directions:

1. Place one sample under the microscope.

2. Focus the microscope so that your sample takes up most of your field of view.

3. Draw in detail what you see in the space provided below. Color your picture and include the magnification! If you have a cell phone with a camera, try to snap a picture of each specimen. It helps to start far away and then bring the camera closer keeping your eyepiece within your camera’s field of view.

4. Draw your other specimen at the same magnification.

Specimen: Specimen:

Magnification: _______________ Magnification: _______________
Station #4: How does a Scanning Electron Microscope work?

Follow the link below to watch this short 5-minute video on the basics of scanning electron microscopy and answer the questions below as you watch. The video is a little bit dated so their microscopes look a bit different than the ones we are using but the basic principles behind the way the machines work is the same.

http://www.youtube.com/watch?v=lrXMIghANbg

1. What is the difference between an ordinary light microscope and a scanning electron microscope? (May be helpful to draw a picture)

2. Draw a diagram of the inside of an SEM (You may have to stop and rewind the video to completely label the diagram)

3. How does coating the specimen with a fine layer of metal help in the imaging process?

4. What does a photomultiplier tube do?

5. What is a secondary electron?

6. What happens when electrons strike the scintillator?

7. Why is it called a scanning electron microscope?

8. Why is the interior of the microscope where the specimen is located a vacuum?
9. Why do they coat their sample in gold palladium plating?

10. How is the way they record an image different from the way we record an image with the Phenom?
Station #5: Purpose and Function of Hair and Feathers

Mini-Lab: How do hair and feathers help organisms regulate their body temperature?

Materials:
4 Zip-lock plastic bags – sandwich size
2 Temperature probes
Ice cubes

Procedure:
1. Prepare bags.
   a. Take one bag and zip it most of the way. Blow air into it to partly fill it up.
      Zip it up.
   b. Leave second bag flat and closed.
   c. Fill remaining two bags with ice cubes. Zip them up.
2. Trial A:
   a. Place probe on the table.
   b. Put bag of air on top of probe.
   c. Record temperature.
   d. Lay bag of ice on top of bag of air.
   e. After 1 minute, record temperature.
   f. Calculate any change in temperature.
3. Trial B:
   a. Place probe on the table.
   b. Put empty bag on top of probe.
   c. Record temperature.
   d. Lay bag of ice on top of empty bag.
   e. After 1 minute, record temperature.
   f. Calculate any change in temperature.

Analysis:
1. What happened to the temperature in trial A?
2. What happened to the temperature in trial B?
3. What did the bag of air represent?
4. What did the empty bag of air represent?
5. How does this activity model the function of feathers and hair in the real world?
Station #6: Powers of 10

Directions: At this station you will find 18 laminated pictures of objects of varying degree of size. There are some things that are very small and some things that are very large.

1. Your group’s first task is to arrange the laminated cards in order from largest to smallest on the lab table.
2. Next you will need to figure out approximate size and write the name of the object next to the correct size below. If it says “object” then one of your 18 objects should go there. If there is no “object” prompt then leave that box blank. An example has been completed for you: Humans are a little bigger than $10^{+0}$ (1 meter) but smaller than $10^{+1}$ (1 dekameter). As you might have figured out – putting them all in order initially will help you fill in the chart.
3. Color code the “tool” column according to what instrument you would use to observe something of that size.

Red = telescope  Blue = Naked Eye
Green = Optical Microscope  Yellow = Scanning electron microscope

<table>
<thead>
<tr>
<th>Size</th>
<th>Object</th>
<th>Tool</th>
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<tbody>
<tr>
<td>$10^{+10}$</td>
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<tr>
<td>$10^{+9}$ (giga-)</td>
<td>Object:</td>
<td></td>
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<tr>
<td>$10^{+8}$</td>
<td>Object:</td>
<td></td>
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<tr>
<td>$10^{+7}$</td>
<td>Object:</td>
<td></td>
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<tr>
<td>$10^{+6}$ (mega-)</td>
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<td>$10^{+5}$</td>
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<tr>
<td>$10^{+4}$</td>
<td>Object:</td>
<td></td>
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<tr>
<td>$10^{+3}$ (kilometer)</td>
<td>Object:</td>
<td></td>
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<tr>
<td>$10^{+2}$</td>
<td>Object:</td>
<td></td>
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<tr>
<td>$10^{+1}$</td>
<td>Object:</td>
<td></td>
</tr>
<tr>
<td>$10^{0}$ (meter)</td>
<td>Object: Example: Human</td>
<td></td>
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<tr>
<td>$10^{-1}$</td>
<td>Object:</td>
<td></td>
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<tr>
<td>$10^{-2}$ (centi-)</td>
<td>Object:</td>
<td></td>
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<tr>
<td>$10^{-3}$ (milli-)</td>
<td>Object: Object:</td>
<td></td>
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<tr>
<td>$10^{-4}$</td>
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<td>$10^{-5}$</td>
<td>Object:</td>
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<tr>
<td>$10^{-6}$ (micro-)</td>
<td>Object: Object:</td>
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<td>$10^{-7}$</td>
<td>Object:</td>
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<td>$10^8$</td>
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<td>$10^9$ (nano-)</td>
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<td>$10^{10}$</td>
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<td>$10^{14}$</td>
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Station #7: Virtual Electron Microscope

At this station you will use one of the laptops and go to the following website (hopefully it will still be on the website from the previous group). There are 10 images that were taken with a scanning electron microscope. A short clue is provided to help you match up the images with the correct object. Good Luck!!
http://school.discoveryeducation.com/lessonplans/interact/vemwindow.html

Specimen #1

Specimen #2

Specimen #3

Specimen #4

Specimen #5

Specimen #6

Specimen #7

Specimen #8

Specimen #9

Specimen #10

*Extension:* Find 3 SEM images on the web that you think the class would have a difficult time identifying and place them on your thumb drive. Place them at the end of your PowerPoint presentation for extra credit. (Hint: don’t use the first thing that comes up on Google because everyone will see those)
Station #8: Scanning Electron Microscope (SEM)

1. For this task you should capture at least 3 images of each specimen under different magnifications determined during class discussion

2. Insert your Thumb-Drive

3. Image Capture
   a. Label images before taking a picture
   b. Check Archive to make sure you have captured all the images you thought you have

<table>
<thead>
<tr>
<th>Sample</th>
<th>Magnification</th>
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<tbody>
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Stations #9 & 10: Presentation Planning

Part 1
- Plan your presentation slides
- Start formatting the slides

Part 2
- Add images and information to PowerPoint

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Your presentation will include the following slides:

Slide 1 – Title
- Title of your project (include what specimens you compared)
- Names of all members of your group

Slide 2 – Question

Slide 3 – Background
- Facts about fur, hair, scales and feathers

Slide 4 – Hypothesis

Slide 5/6 – Images side by side
- Remember to include the following:
  - Scale bars
  - Labels
  - Magnification
  - Tool specifications

Slide 7 – Data Analysis
- Compare and Contrast specimens

Slide 8 – Conclusion
- What did you learn

Slide 9 – Error analysis
Scales Explained

Let’s examine scales that we find on many fish and reptiles. Both are made up of the protein Keratin and ultimately aid fish and reptiles in very similar ways. Fish scales seem to help the fish in several ways. They provide a protective covering to keep harmful things out of the fish's body. Scales allow the fish to move. Scales are hard structures, but there are so many of them and they are positioned one atop the next in such a way that they can slide past one another so the fish can move its body up and down and side to side to swim. It seems that they are also designed so that water can move across them easily so they do not slow down the fish.

Fish scales are composed of connective tissue covered with calcium. Typically, soft-rayed fish have smooth cycloid scales and spiny-rayed fish have ctenoid scales.

Scales can be used for aging fish. The annulii, or growth rings like on trees, are counted from the focus (where growth starts) outward. By measuring the distance between annulii, along a radius, the growth rate of the fish can even be estimated.

Reptiles also have scales however their primary purpose of scales on reptiles is to prevent dehydration in dry air. Reptiles have dry, scaly skin. But they don't need moisturizer! Their special covering actually helps them hold in moisture and lets them live in dry places. Reptile scales are not separate, detachable structures -- like fish scales. Instead, they are connected in a "sheet," which is the outermost layer of skin. Every so often, this layer of skin is shed and replaced. In some reptiles the skin flakes off in chunks. In snakes, the skin is usually shed in one piece. What about turtles and tortoises? You may not think of their shells as being scaly, but they are! They are complex structures made up of bones and scales that develop from the outer layer of skin. It's natural body armor! As you might have guess, scales also help protect reptiles just as scales on a fish do.
Feathers Explained

Have you ever seen a bird without feathers? Today, all birds have feathers and birds are the only animals with feathers. Bird feathers are amazingly complex. Each feather is made from the protein Keratin. The three main types of feathers are the **filoplumes** (sensory feathers), the **contour feathers** (flight feathers), and the **down feathers** (insulation feathers).

One of the reasons bird feathers are so complex is that each feather is made up of many different parts. The feather is similar in many ways to a palm frond. The rachis (same as in palms) is the central core. The area that the feather attaches to the bird is called the calamus. The rachis has barbs that extend from it, which collectively make up the vane. Along the feather, each barb has a shaft called a ramus. From each side of the ramus are barbules and barbicels. In essence they act like modern day Velcro. One side can hook onto the other and keep the wing stiff. As a kid I’m sure everyone has run their fingers the wrong way down a bird feather and separated them. Birds can ‘zip-up’ their feathers by running them the other way and in essence, re-hooking the barbules and barbicels.

Down feathers are slightly different than flight feathers because they do not have barbules on them even though they still have some of the same structure as a normal feather. They are normally very soft because they lack the stiff barbs. Many types of birds have modification to their feathers for specific purposes. Owls for instance have velvet-like projections that extend from their feathers that allow them to fly silently. Another example is the Sand Grouse that lives in desert locations and has feathers with highly curled barbs. These barbs will hold water when a bird dips into an oasis. This allows the bird to then fly back to the nestlings and they can drink from the bird’s breast.

So the question comes to mind, besides flight what is the main purpose of feathers? Many male birds use distinct marking and colors that determine how attractive he is to a female and his mating success. Male birds are often brighter and more colorful than female birds for this purpose. Feathers also regulate body temperature as they help to keep birds warm and dry. Penguin feathers are especially well adapted for this purpose. The feathers are small and densely packed. The downy base of each feather traps an insulating layer of air against the penguin’s skin. The feather tips overlap each other to form a waterproof outer shield. As with many other species, penguins preen to keep their feathers clean and waterproof. Oil from a gland at the base of the tail helps to waterproof the feathers. As a penguin preens, it spreads the oil throughout the feathers, and in the process cleans and smoothes them. Finally, the colors of a bird’s feathers are often used to provide camouflage from potential predators. This may include molting during different seasons to blend in with the surrounding (such as snow), or countershading (dark above, light below) to make it harder to see.
Fur and Hair Explanation

It has been heavily debated, but it seems that most scientists agree that hair and fur are the same thing. One of the unique characteristics of a mammal is that they have hair or fur which is made up of the protein keratin. Like feathers, hair and fur insulates to help animals maintain a warm and constant body temperature. In addition, hair and fur can help camouflage animals from predators or to blend into their environment when stalking prey.

Hair is held in place below the skin by a root situated in a shaft surrounded by a hair follicle. Each hair shaft has an inner layer of cells called the medulla or pith, containing soft keratin. The next layer is called the cortex, which is a semi-transparent, thick layer that contains "hard type keratin" filled cells. It occupies the bulk of the hair. The cortex contains scattered pigment cells that produce melanin, giving hair its color. The outer layer of the hair shaft, the cuticle, consists of a single layer of colorless keratinized cells that cover the hair somewhat like skin. These hardened, flat cells overlap like house shingles.

Most fur consists of two layers–underfur, the short, soft, curly hair next to the skin and guard hair, the longer, stiffer hairs covering the underfur. These two layers, together with the skin, make up the pelt. Fur keeps animals warm because the hairs retain a layer of air that serves as insulation against the cold.

Animals grow heavy, thick coats of fur during cold winters and at high altitudes, and thinner coats in warmer areas. Animals in snowy regions are generally light in color; those in warmer, forested areas are usually of a darker shade. Changing seasons also affect fur. Animals that become dormant in winter eat heavily and have fur of excellent quality in fall; when they awaken, they are thin and their fur is faded.
What is the difference between hair and fur?

*Scientific American* writer Kate Wong spoke with mammalogist Nancy Simmons of the American Museum of Natural History in New York City about this question. An edited transcript of the interview follows.

Tuesday, February 20, 2001

**SA:** Is there a difference between hair and fur?

**NS:** There isn’t. Hair and fur are the same thing.

**SA:** Why is it than that, for example, my dog’s fur is three inches long and it never seems to grow longer, while my own hair keeps growing and growing?

**NS:** Actually, a lot of types of human hair won’t keep growing and growing. The normal length of the hair is an individual and species specific trait. So across the breadth of mammals, there are many norms for hair length, or fur length.

What’s really different is the pattern of where it grows. Your dog or cat is basically covered with hair, whereas humans tend to grow hair in a few selected places. And that’s one of the things that have changed through evolution in a number of mammal groups. Whales, for instance, are mammals, but they are nearly hairless. We lack hair over a lot of our bodies.

**SA:** Is hair a defining characteristic of mammals?

**NS:** It’s one of them. Other features that define mammals include producing milk to nourish the offspring.

**SA:** When does hair appear to have arisen?

**NS:** We don’t know, because the evolutionary lineage leading to mammals includes many fossil forms going way back in time, and hair, as a rule, doesn’t fossilize. So we can’t know whether many of these relatives of mammals from the age of dinosaurs and earlier had hair or not.

**SA:** Are there any impressions of hair in the fossil record?

**NS:** There are very few fossils where there are impressions of anything in terms of soft tissue.

**SA:** How did hair evolve?

**NS:** I think most evolutionary biologists believe that the evolution of hair is correlated with the evolution of endothermy, or warm bloodedness (the ability to produce internal body heat) and hair is a very good insulator. If you’re going to spend a lot of metabolic energy heating your body, it’s more efficient to hold on to that heat and not to lose it to the environment around you. So having hair as a means of insulation is one of the ideas about why we have hair. Of course, there is no way for us to tell whether hair evolved
first and then endothermy evolved, or whether endothermy evolved and then somehow
hair evolved. We really don’t know anything about these things.

**SA: Humans evolved in Africa, along with a lot of primates that are covered with
fur. Why did humans lose most of theirs?**

**NS:** We don’t know. There’s a lot of variation in how much of the body is covered with
fur in various primate groups. Some are incredibly hairy, and some have considerably
less fur on the face and the chest and so on. Primates tend to rely on facial expressions for
social communication, and of course the better you can see the face, perhaps the better
that social communication works. That doesn’t mean you have to get rid of the hair to see
the face. That just happens to be what happened in apes. But that could be one of the
reasons why we don’t have hair on our faces.

**SA: Is a whisker a special kind of hair?**

**NS:** Yes, it is. There are many different kinds of modified hairs to which we give
different names. A porcupine’s quills are greatly enlarged hairs. Whiskers are hairs that
work as sensory receptors. There’s a strange animal from the Old World called a
pangolin, which has these scaly plates that cover most of its body, those are modified
hairs.

**SA: So this is all the same material?**

**NS:** This is all the same material.

**SA: How does a whisker work as a sensory receptor?**

**NS:** It has to do with its size, and whiskers have special nervous connections that make
them highly sensitive to movement. Those nerves are directly connected to a part of the
brain that keeps track of that information and allows the animal to interpret it as sensory
information in conjunction with the other information it’s getting from adjacent whiskers.

**SA: When you see something that looks like a whisker on a catfish, for example,
what is that structure?**

**NS:** Well, it’s a similar structure in the sense that it is a long, skinny thing that sticks out
from the body and is used to help sense what’s going on in the environment. But it’s not
homologous; it’s independently evolved. It’s not made of the same material, and it wasn’t
inherited from a common ancestor. It’s a completely different structure that may serve
something of the same purpose, but completely independently.
We may think about human hair, curly versus straight versus whatever, as being really
different from what animals have, but if you think of the breadth of mammals out there
you can find equivalents in many other groups for long hair versus short hair versus
tightly curled hair and all that. You can actually find all of that in dogs, without even
having to look to other species.

Permanent Address: http://www.scientificamerican.com/article.cfm?id=what-is-the-difference-be
Our hair is rooted in reptilian claws, according to a new study that revealed hair genes in both lizards and birds.

Previously, scientists thought hair first appeared in mammals.

Hair, which provides insulation and protection, is seen as one of the main evolutionary innovations that led to the rise of mammals.

But the origins of hair date back to an unknown reptile ancestor that lived more than 300 million years ago, in the Paleozoic era, the new study says.

A team led by Leopold Eckhart of the Medical University of Vienna in Austria made the discovery by comparing human, chicken, and green anole lizard genomes.

The genome of the lizard was found to contain six different genes for hair keratin, the protein from which mammal hair is made.

The genes were expressed most strongly in the lizard's toes, indicating that the first hair genes played a role in claw formation, the study team reports in tomorrow's issue of the Proceedings of the National Academy of Sciences.

"At least two of these hair protein keratins are formed in the growth zones of the claws," Eckhart said.

While the role of the anole lizard's four other hair genes remains unclear, they were likely related to the growth of scales, the study team said.

The chicken genome revealed a single hair gene. It's unclear what that gene is for, if anything.

Hair-Raising Creatures

The finding suggests that modern birds, reptiles, and mammals—as well as dinosaurs—shared an early common ancestor that had claws built from hair keratin, Eckhart said.

"Actually, it may be more appropriate to call these proteins claw keratins, which later acquired an additional role in hair," he said.
Eckhart speculates that hair evolution began with claw keratins that were later adapted to form scales, from which the earliest hairs then developed.

The very first whiskery hairs may even have sprouted on reptiles, Eckhart said.

"However, I don't think it very likely," he added.

"If they were present, I wonder why modern reptiles don't have them anymore. If hairs were useful, they wouldn't have lost them."

Günter Wagner, a professor of evolutionary biology at Yale University, said the new study shows that that hair growth wasn't just a matter of having keratin genes.

Only in mammals, however, did keratin evolve into strands.

"The standard theory was that you get hair when you get the hair-specific keratin, but the problem was [actually] how to pack those keratins into very long and thin structures," Wagner said.

Similarly, he said, a recent study showed that birds shared feather-making keratins with an ancient, featherless ancestor of crocodiles.

Microscopes – Helping Scientists Explore Hidden Worlds

The microscope is an invaluable tool in today's research and education. It is used in a wide range of scientific fields, where major discoveries in biology, medicine and materials research are based on advances in microscopy. As the need to see the world at a smaller and smaller scale has grown scientist looked for ways to improve on the light microscope (see Fig. 1 below).

In 1938 Ernst Ruska developed the electron microscope and in 1981 Gerd Binnig and Heinrich Rohrer invented the scanning tunneling microscope that gives three-dimensional images of objects down to the atomic level. In 1986 all three men received the Nobel Prize in Physics. The greater resolution and magnification of the electron microscope is because the wavelength of an electron; its de Broglie wavelength is much smaller than that of a photon of visible light. Conventional light microscopes use a series of glass lenses to bend light waves and create a magnified image. The electron microscope uses electrostatic and electromagnetic lenses in forming the image by controlling the electron beam to focus it on the surface of the specimen. The SEM shows very detailed 3-dimensional images at much higher magnifications than is possible with a light microscope (because electrons travel at a smaller wavelength) but the images are in black and white because electrons don't give off visible light (see Fig. 2 below).

To prevent electrons from colliding with air molecules all SEMs work under a vacuum. Initially samples are stuck down on a metal stub and have to be prepared carefully to withstand the vacuum inside the microscope. **No wet, magnetic or live samples can go into an SEM.** Biological specimens are first dried in a special manner that prevents them from shriveling. Also because the SEM illuminates with electrons, they also have to be made to conduct electricity. SEM samples are often coated with a very thin layer of a metal (i.e. gold) by a machine called a sputter coater. Once the specimen is prepared its ready to go into the SEM, the sample is placed inside the microscope's vacuum column through an air-tight door. This is the most important part of the entire procedure because this is where machines can be damaged. You must make sure everything is stuck to your metal stub by blowing it off with compressed air. When inserting the specimen into the cup you must turn it down until it is flush with the top of the cup, and then rotate four more clicks on the cup. Finally the sample can carefully be placed into the machine and the door shut.

After the air is pumped out of the column, an electron gun [at the top] emits a beam of high energy electrons. This beam travels downward through a series of magnetic lenses designed to focus the electrons to a very fine spot. Near the bottom, a set of scanning coils moves the focused beam back and forth across the specimen, row by row, this is called rastering. As the electron beam hits each spot on the sample, secondary electrons are knocked loose from its surface. A detector counts these electrons and sends the signals to an amplifier. The final image is built up from the number of electrons emitted from each spot on the sample. A problem that often arises is that a specimen will become overly charged with electron causing your image to appear white – we will discuss this issue as it comes up.
The Scanning Electron Microscope is revealing new levels of detail and complexity in the amazing world of micro-organisms and miniature structures.

Homework Questions:
1. Can you use an SEM to get an image of the surface of an iron nail? Why or why not?

2. How many clicks do you rotate down after you have made the object flush with the metal cup?

3. What actually makes the image of the sample?

4. What instrument(s) can you use to see an image of a cell?

5. When was the first electron microscope developed?

6. How does the SEM prevent air molecules and electrons from colliding?

7. What must you do to a sample once it is on the stub before inserting it into the machine?
Power of 10 Images and Teacher Key

<p>| | | | | | | |</p>
<table>
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</tbody>
</table>
## List of Objects:

<table>
<thead>
<tr>
<th></th>
<th>Sun</th>
<th>Moon</th>
<th>Human</th>
<th>Bacteria</th>
<th>Red Blood Cell</th>
<th>Ant</th>
<th>Chicken Egg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecule</td>
<td>VD</td>
<td>Atom</td>
<td>State of Oregon</td>
<td>United States</td>
<td>Hurricane</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atomic nucleus</td>
<td>Diameter of DNA structure</td>
<td>Water</td>
<td>Football field</td>
<td>Thickness of a nickel</td>
<td>Thickness of Human hair</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Class Discussion Prompts

1. Connection between observation of similar structures and evolution.
2. New technology (such as SEM) can shape scientists understanding of concepts.
3. Appreciation for the different scales of the world around us.
4. Structure doesn’t always dictate function.
### Annie’s Content Representations (CoRe) table

The following CoRe table A.8 was created in collaboration with the same experienced teacher and student teacher she worked with to create their unit of instruction. Here is this group’s CoRe along with a column that contains researcher memos and codes. Please note that the participants color coded particular rows for the purposes of their own discussion and reflection and that these colors are left intact as presented by the teachers in the group.

#### Table A.8 Content Representations Table:

<table>
<thead>
<tr>
<th>This CoRe is designed for: (course name &amp; grade level)</th>
<th>Important Science Idea/Concepts</th>
<th>Researcher Memos &amp; Codes</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. The structure of feathers, fur, scales, and hair are virtually the same.</td>
<td>B. The function of feathers, fur, scales, and hair are variable.</td>
<td>D. There is an evolutionary advantage to structure and function of an organism's feathers, fur, scales, and hair.</td>
</tr>
</tbody>
</table>

#### Annie, one veteran high school teacher and one student-teacher

| What you intend the students to learn about this idea. | Upon magnification, students will see similar structure in feather, fur, and hair. | Upon investigation students will start to understand that structure can differ from function. | When examining organisms with either fur, feather, scales, or hair, student will be able to recognize the advantage to having each type of "covering" | Successfully use the SEM to collect images that can be used to draw conclusions. |

| Why is it important for the students to know this? | Although things appear to be very different on a macro scale, when investigated at a micro level there are similarities. | Students will connect common structures can serve different functions depending on environmental conditions which allows for a hypothesis that organisms have common ancestors. | As junior high students, it is important to introduce the concept of adaptations and evolution so it can be built upon at the high school level. Evolution is also a paramount theory in science. | It is important that students realize that scientific equipment isn't just to be touched and manipulated by professionals. We are all scientists and thus can make discoveries and gather data if given the right equipment. |

| What else do you know | That fur, | That fur, | The order at which | The SEM will |

<p>| Evolutionary advantages | Structure and function | SEM skills | Differences between structure &amp; function | SEM/inquiry skills | Finding similarities | Scaffolding adaptations | Nature of science | Evolution of fur &amp; |</p>
<table>
<thead>
<tr>
<th>About this idea (that you do not intend the students to know yet?)</th>
<th>Feather, hair, and scales are all structurally the same.</th>
<th>Feathers, and hair have evolved from scales.</th>
<th>Most scientists agree that these structures have evolved.</th>
<th>Feathers from scales</th>
<th>Curiosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Learning opportunities made possible with the use of technology</td>
<td>Being able to see things that the naked eye cannot see.</td>
<td>The ability to see pictures of animals from different environments via the internet to see significant differences in function.</td>
<td>Students are able to see what they could not see with their naked eye making something that looks very different such as hair and feathers look very similar with the right magnification with an SEM. This could be used to make evolutionary connections.</td>
<td>Being able to see things that the naked eye cannot see.</td>
<td>Affordances of technology</td>
</tr>
<tr>
<td>Difficulties/limitations connected with teaching this idea:</td>
<td>Collecting feathers is illegal. Access to SEM and safe use of equipment by students. Adequate time to complete activity.</td>
<td>Collecting feathers is illegal. Access to SEM and safe use of equipment by students. Adequate time to complete activity.</td>
<td>Collecting feathers is illegal. Access to SEM and safe use of equipment by students. Adequate time to complete activity.</td>
<td>Collecting feathers is illegal. Access to SEM and safe use of equipment by students. Adequate time to complete activity.</td>
<td>Sampling limitations</td>
</tr>
<tr>
<td>Common misconceptions students hold about this idea:</td>
<td>Feathers, fur, scales, and hair are all structurally different.</td>
<td>Feathers, fur, scales, and hair have multiple functions.</td>
<td>Adaptations can be controlled by an individual.</td>
<td>SEMs are only found in high tech labs.</td>
<td>Misconceptions about structure differences</td>
</tr>
<tr>
<td>Knowledge about students' thinking which influences your teaching of this idea</td>
<td>Students think all structures are different.</td>
<td>Understanding function allows us to make connections to evolution.</td>
<td>Some students have non-positive attitudes when it comes to the concept of evolution.</td>
<td>Students feel technology is exciting.</td>
<td>Affordances of understand function</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Student attitudes</td>
</tr>
<tr>
<td>Knowledge about students’ thinking that influences how you integrate technology into the lesson</td>
<td>Not all students are primarily visual or kinesthetic learners, some students might be hesitant to use technology if they do not feel comfortable working with new technology or expensive equipment.</td>
<td>Not all students are primarily visual or kinesthetic learners, some students might be hesitant to use technology if they do not feel comfortable working with new technology or expensive equipment.</td>
<td>Not all students are primarily visual or kinesthetic learners, some students might be hesitant to use technology if they do not feel comfortable working with new technology or expensive equipment.</td>
<td>Students’ hesitancy to work with new, expensive SEM and beliefs about evolution Wow factor</td>
<td></td>
</tr>
<tr>
<td>---</td>
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<td>---</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>Other factors that influence your teaching of this idea.</td>
<td>Time that students have to find the images that they want to capture. It is very hard to find what you want in only 15 minutes, especially if you want to split that time with multiple students.</td>
<td>Time that students have to find the images that they want to capture. It is very hard to find what you want in only 15 minutes, especially if you want to split that time with multiple students.</td>
<td>Time that students have to find the images that they want to capture. It is very hard to find what you want in only 15 minutes, especially if you want to split that time with multiple students.</td>
<td>Time constraints Classroom management</td>
<td></td>
</tr>
<tr>
<td>Teaching procedures (and particular reasons for using these to engage with this idea.)</td>
<td>Viewing through a SEM allows us to view structure at a level not typical for most. Comparing animals with similar covering that live under different environments demonstrate differences in function.</td>
<td>Reading about the evolutionary order that is accepted and seeing images that support similarities in structure at a microscopic level, yet appear very different at the macro level.</td>
<td>Students need to compare their images at the same magnitude in order to make valid claims.</td>
<td>Multiple modalities of learning Comparing images at multiple scales</td>
<td></td>
</tr>
<tr>
<td>Specific ways of ascertaining student’s understanding or confusion around this idea (include likely range of responses.)</td>
<td>Students will be present a PowerPoint presentation at the end of the unit and turn in their packet of station work.</td>
<td>Students will be present a PowerPoint presentation at the end of the unit and turn in their packet of station work.</td>
<td>Students will be present a PowerPoint presentation at the end of the unit and turn in their packet of station work.</td>
<td>Power Point summative activity Teacher at SEM Help as needed</td>
<td></td>
</tr>
</tbody>
</table>

CoRe template developed by Loughran, Berry and Mulhall (2006).
Analysis of Annie’s Thinking

Due to the way the SEM schedule worked out, Annie said at the beginning of a classroom observation that she taught geologic time and plate tectonics in the unit directly before this unit and planned to continue with this topic following the conclusion of the Project NANO unit. She shared that the students were explicitly told that they were going to do a unit out of sequence due to the opportunity provided by Project NANO to get the SEM in their classroom. They were told that the content covered in the unit would not be approached again until the spring and that the major learning outcome goals of the unit was to support the development of scientific language, drawing and photographic skills used to capture and describe observations using scientific procedures involving the use of scientific tools.

The big ideas in nanoscale science addressed in Annie’s unit are: size and scale, structure of matter, tools and instrumentations and science, technology and society. These data inform the first part of the sub-question, of the nine “big ideas” in nanoscale science and technology, which are the big ideas that teachers choose to teach in their Project NANO unit and why?

As for the second part of that sub-question, Annie said during a classroom observation that her decision as to which big ideas to teach in the unit was partially influenced by the competition to sign up for the SEM. She reported that since she wasn’t able to sign up for the SEM dates prior to planning the unit, she planned with the idea that she would be able to get the SEM sometime in the fall. Therefore, she chose “somewhat generic learning goals” that were to a large degree dictated by what is
normally taught at the beginning of the school year according to both the textbook and her past experience as a middle-level science teacher. This is a time when foundational scientific laboratory procedures are taught and re-enforced, so she knew that regardless of when she actually got the SEM in her classroom, she could adjust her unit to teach laboratory skills.

Annie clearly built upon her PCK by working within laboratory group during the summer workshop. Indeed, all three of the members of the group reported how discussions and group experiments with samples and microscopes built their own PCK. For example, Annie described during her interview and during the workshop how the Critical Friends Tuning Protocol activities informed her own thinking about how to frame ideas, how to order experiences and how to choose activities that teach and re-enforce specific skills and concepts. After learning about how to use this model to constructively evaluate someone else’s unit, the lab groups integrated this thinking into developing their own unit of instruction plan and setting criteria for the elements they need to include.

Annie said during her interview that the way she experienced this process was that:

The questions on the CoRe template facilitated group discussions that led to choosing the big ideas and unpacking our thinking about why and how to teach those particular ideas. The unit of instruction template then facilitated discussion about how to organize our content and experiences and why. This way we weren’t just putting the SEM in the middle but putting the students and content learning goals in the middle of our planning.

**Annie’s Pre and Post survey scores.** Just as Annie’s reflective ideas communicate growth, Annie’s pre and post survey demonstrates that she gained nanoscale science content knowledge as a result of her participation in the workshop. Because Annie participated in the first of three workshops sessions, she took the pre and
post survey that includes four open-ended questions and no multiple-choice items.

Again, the teacher’s writing was scoring using the locally developed rubric used for the workshop. The following reports data that informs the sub question, *do teachers demonstrate scientific content knowledge gains in response to the 2012 Project NANO summer workshop?*

The following table A.9 presents Annie’s pre and post survey scores:

**Table A.9**

**Annie's Pre & Post Survey Scores**

<table>
<thead>
<tr>
<th>Pre – Post Survey Questions</th>
<th>What is the difference between an optical microscope and an SEM”</th>
<th>Describe 5 key components of the scanning electron microscope (the mechanics of the tool)</th>
<th>Describe safety protocols related to working with secondary level students and a table top SEM</th>
<th>Provide a brief description of how you might integrate optical and electron microscopes in a course to instruction students on form and function related to the discipline you teach.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre Survey</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Post Survey</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

Annie improved in her ability to accurately describe the difference between an optical and electron microscope by one point because she added a description of the SEM. She moved from being unable to accurately name any parts of an SEM to accurately naming five key parts, and improved in her ability to briefly describe ideas for how she may include nanoscale science and technology into the curriculum. However,
she did not show change on a question related to laboratory safety, listing only ideas for how to keep the very expensive SEM safe from students on both the pre and post survey.  

**Annie’s Knowledge, Skills, Experiences, Community and Assessment Scoring Guide scores.** The Furs, Feathers and Scales unit was assessed using the unit plan scoring guide. Overall Annie’s unit scored 51 of 64 possible points. The following table A.10 shows Annie’s scores for each of the elements of her unit of instruction.  

**Table A.10**  

**Annie’s Unit of Instruction Scores**  

<table>
<thead>
<tr>
<th></th>
<th>Knowledge &amp; Skills</th>
<th>Sci. Inq. &amp; Eng. Design</th>
<th>Experiences</th>
<th>Community</th>
<th>Assessment</th>
<th>Total Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre Survey</td>
<td>10</td>
<td>12</td>
<td>8</td>
<td>12</td>
<td>9</td>
<td>51</td>
</tr>
<tr>
<td>Post Survey</td>
<td>12</td>
<td>15</td>
<td>8</td>
<td>12</td>
<td>10</td>
<td>57</td>
</tr>
</tbody>
</table>

This unit scored 10 of 12 points on the pre-survey on the *knowledge and skills* category, losing two points because some of topics addressed in the unit fits better with the high school biology content standards then eighth grade integrated science standards. Otherwise, the unit clearly expressed, in student friendly terms, learning objectives with links to prior learning.  

In the *science inquiry and engineering design* category, the unit scored all the points possible for categories related to designing and implementing an inquiry.
However, the unit lost three points for lacking clear opportunities to develop scientific argumentations skills by publically defending scientific claims or observations.

Because clear connections were made in the unit between the content, technical applications of the science in manufacturing and medicine and bio-ethics, the unit scored three of three points in the student experiences category of the student experiences curriculum element. But the unit lost a few points due to a lack of any explicit mention of culturally relevant instructional strategies and ideas for how her formative assessments influence instructional differentiation. Two ideas were presented to students as optional extensions. The first extension idea, pursued by most of the students in the high-ability class and many in the lower ability class, was to alter images (improve photo micrographs) using the Image J software. The second was a brief reference to the idea of using the SEM for a science fair experiment, an idea she and her students did not pursue.

Annie’s unit scored all of the points possible in the learning community section. The unit design includes small collaborative work groups pursuing an inquiry process drawing on what they know and know how to do in preparation to communicate and defend their results in the form of an individually grade report and a presentation of data.

Student assessment tools described in the unit plan were almost entirely summative instruments, thus the unit scored three of three points on the post-assessment category, but only one of three points in two other categories because the chosen tools fail to inform teacher and students thinking throughout the unit. Prior knowledge was briefly activated in some of the stations to the level of understanding and low-level problem solving, thus scoring two of three points. And finally, student work samples
were used as part of the summative assessment. The stations and student work packet were designed to provide students with opportunities to develop and demonstrate understanding. However, the work packets also restricted students’ freedom of how to log, format and present data, thus preventing Annie’s unit from scoring three points instead of two points.

When asked during the workshop why she chose to use mainly summative assessment strategies, Annie said that since she knew that she would be “stuck” at the SEM throughout most of the unit, she took care to plan a large number of station activities each with student worksheets she could read to periodically check student understanding. She wanted to ensure that every student had something to do at all times while groups did 20-minute rotations on the SEM and the Leica. So worksheets served the dual purposes of allowing students to be divided up at multiple stations without direct teacher support and providing a way for the teacher to check student thinking.

Annie said during classroom observations and in her interview that in a normal situation where she is not stuck at one station, she would be more likely ask the students to create interactive science journals and rely more on frequent formative assessment probes and discussion prompts at stations rather than use student worksheets and independent lab activities. However constraints imposed by the SEM radically shifted her practices to be more structured and directive, thus shifting from a learning centered approach to a teacher directed approach.

**Annie’s classroom observation scores.** Three classroom observations were conducted in the fall. Each of the classroom observation scored a three using the EQUIP,
which is the level of proficient inquiry. The class consisted of 33 students who were consistently highly engaged throughout each of the observations. The teacher requested that the researcher observe in her lower ability level class as well to get a sense of comparison as to how the two groups of students were responding to the same lesson. In this case, at least half of the students were off-task while one or two lab group members appeared to do the work at each station. The teacher viewed this off-task behavior in multiple ways. She said that the students who were off-task have generally low reading abilities and may not have been able to decipher the instructions at each station. She also pointed out that the parent volunteers are not scientifically trained and often confused students when they attempted to answer questions. Either that or they stepped in and completed the station task for the child, causing several children to lose interest in thinking about the task.

In contrast, the high-ability class appeared to be able to work more independently at each station to decipher the instructions, record data, complete the station tasks and write reflections that connect the activity to the big ideas. The teacher reported between classroom observations that it took her several days to feel confident that she knew the controls on the Leica well enough to train someone else, but that once she and the parents figured out the controls together, she asked the parents to primarily support students at the Leica and sample preparation stations. Thus she solved a technical and pedagogical problem for one of her classes by having prepared volunteers at the only problematic stations for the high-ability group. However she asked that Project NANO consider training adult volunteers to manage the SEM so that she can circulate throughout the
classroom supporting students through each of the lab stations, thus solving problems for both levels of classes.

Annie wrote in her CoRe that the investigation of fir, feathers and scales provided students with some degree of flexibility in the questions they asked and how they pursued as their investigation. At the same time, the structure of the cyclical rotations through stations built knowledge in a way that provided clear links between the concepts addressed in each activity and the big ideas. The teacher said during her interview that she consistently functioned as a facilitator at the SEM and occasionally with students at the other lab stations when either the researcher or the Project NANO coach was able to supervise students at the SEM. At the SEM, it was observed that the teacher’s probes required students to describe their observations, make claims drawing upon their rationales and scientific language to justify their thinking. However there was little observed scientific argumentation between students either at the SEM or at any other station.

Although the primary form of assessment was the process-focused student worksheets, however they were only checked by the teacher periodically and they were not used as a formative assessment tool to guide metacognitive reflection on the part of the student. The teacher however, did report during her interview ways in which she shifted instruction between class days based on student’s writings. For example, after the first lab day, she said that she rewrote each of station instructions to make them more clear for students and she followed the lead of her Project NANO coach and shifted to asking the group “on deck” waiting to get on the SEM questions to ensure that they
understood the procedural steps. She also learned specific “tips and tricks” when her coach visited her classroom such as what questions to ask students about the texture, shape, size or luster of samples or words used to elicit student thinking about observations made at various scales.

The theme of solving technical difficulties came up repeatedly in both the classroom observations and teachers reflections. Here I will describe what happened in the classroom to negotiate technology and in the next section I will describe the teachers’ thinking as evidenced by her reflective writings and interview statements.

Annie reported that it felt like a really long time between the summer workshop and November when she taught the Project NANO unit. She said that she lost sleep in October worrying that she had forgotten all of the controls on both microscopes, she would break the microscopes and that every child would forget to bring their thumb drives to save their images.

As it turned out, her coach visited her the day before she started the unit and they spent a few hours together going over sample preparation, sample load protocols and controls for both of the microscopes. She shared before the start of the second classroom observation that her coach specifically described and reminded her of scientific terminology she should use throughout the process and what instructional moves she should physically model for the students before allowing them to operate the SEM or Leica. After that, she said that her nightmares about safely operating the SEM went away, however she shared that it took her full three days into the lesson to feel confident that she knew how to clearly step a new user though using the SEM. Once she gained
this confidence and relaxed into the repetition of procedures, she said she began to feel bored and found it difficult having to enthusiastically guide each new group through the steps with new zeal for the images each time. She described that she felt frustrated that she couldn’t leave the SEM to help at other stations and worried that students were not getting the help they needed:

My biggest challenge teaching this unit had to do with classroom management. I felt really pressured to stay by the Phenom the entire time and it made it hard for me to monitor what kids were doing and the quality of their work. Looking at the presentations, I feel like the quality is not what I typically expect and get from students. I didn’t have as much time as I would have liked to discuss with the class what they were seeing at the different stations and how each station connected to the big picture.

During the interview, she said that, "the Leica nightmare continued however". After a couple of days in the unit, she was unsure about how to use the controls especially the fine focus and image capture functions, “I had a lot of problems with the Leica microscope. Sometimes it worked and sometimes it didn’t. I didn’t feel really confident in how to work it consistently and therefore couldn’t offer suggestions to frustrated students or parent volunteers.” Her parent volunteers showed up during the five-minute passing period to prepare to help, so Annie said following a classroom observation that she felt tremendous pressure to teach the volunteers something about the microscope with very little time to do it.

Eventually a parent figured out the microscope and the idiosyncrasies of the SD card and taught the teacher and students what she figured out. Annie shared in her interview that by the third day all of the students remembered to bring in their unformatted thumb drives. So basically it took the class three days into a ten-day unit to figure out the technology and prepare their samples on slides and stubs. Thus a
significant unintended learning outcome was that the parents, teacher and students all
developed problem solving strategies that will be applicable to multiple situations
involving microscopes and possibly other digital technologies. Plus, Annie shared during
her interview that she learned that next time it would be best to do sample preparation
prior to the delivery of any instruments, thus lessening the sense of urgency and
frustration around learning a critical step in doing science.

**Annie’s CoRe Call-outs.** Annie approached her call-out reflections by writing
one response for several, but not all of the prompts on the CoRe. In this case, Annie’s
call-out reflections were likely to have been more influence by the interview we had just
before she wrote her call-outs, one week after teaching her nanoscale science unit of
instruction.

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**Project NANO Workshop**
**Summer 2012**
**Content Representations (CoRe) Call-outs**

<table>
<thead>
<tr>
<th>This CoRe is designed for: 7th and 8th grade science “Annie”</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Big Ideas</strong></td>
</tr>
<tr>
<td>A. The structure of feathers, fur, scales, and hair are virtually the same.</td>
</tr>
<tr>
<td>B. The function of feathers, fur, scales, and hair are variable.</td>
</tr>
<tr>
<td>C. There is an evolutionary advantage to structure and function of an organisms feathers, fur, scales, and hair.</td>
</tr>
<tr>
<td>D. Develop the skills necessary to operate a scanning electron microscope. Explain how technology, such as the SEM, can change scientific explanations and</td>
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<td></td>
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<tr>
<td>Theories</td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Missed big picture</td>
</tr>
<tr>
<td>Lack of connection</td>
</tr>
<tr>
<td>Later tie-in?</td>
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<td></td>
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<td></td>
</tr>
</tbody>
</table>
Evidence of Changes in Annie’s Thinking

Three categories developed from the CoRe, call-out reflections and one-hour, one-on-one interview. The following description presents Annie’s PCK and inform the research question how do teacher participants in the 2012 Project Nanoscience and Nanotechnology Outreach (NANO) program negotiate the inclusion of novel science and

<table>
<thead>
<tr>
<th>Category</th>
<th>Reflection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evidence of Changes in Annie’s Thinking</td>
<td>Three categories developed from the CoRe, call-out reflections and one-hour, one-on-one interview. The following description presents Annie’s PCK and inform the research question how do teacher participants in the 2012 Project Nanoscience and Nanotechnology Outreach (NANO) program negotiate the inclusion of novel science and</td>
</tr>
<tr>
<td>Other factors that influence your teaching of this idea.</td>
<td>Classroom management is the key to success is a middle school classroom and I felt very frustrated and overwhelmed with this project, mostly because of the way I had structured it with stations and the fact that I had to be stationed by the Phenom and couldn’t circulate the way I would have liked. The best classes were the ones [when my coach] came to visit and ran the Phenom for me so that I could help out the other students.</td>
</tr>
<tr>
<td>Teaching procedures (and particular reasons for using these to engage with this idea).</td>
<td>I like the idea of having various activities that the students can work on to learn more about related topics. I need to plan on more time to help students to connect the dots between the various activities and ideas they are exploring.</td>
</tr>
<tr>
<td>Specific ways of ascertaining student’s understanding or confusion around this idea (include likely range of responses.)</td>
<td>While I had the students doing activities each day, I didn’t collect them and evaluate them until the end of the unit. It was clear that a lot of students missed information or key concepts.</td>
</tr>
<tr>
<td>Building upon foundational experiences</td>
<td>Frustration</td>
</tr>
<tr>
<td></td>
<td>Overwhelmed</td>
</tr>
<tr>
<td></td>
<td>Structure didn’t function well</td>
</tr>
<tr>
<td></td>
<td>Best class with coach</td>
</tr>
<tr>
<td>Like activity stations idea</td>
<td>Plan more time to assist students connecting concepts</td>
</tr>
<tr>
<td>Students missed key information</td>
<td>Waited too late to assess student progress/thinking</td>
</tr>
</tbody>
</table>

CoRE template modified from a template Created by Loughran, Berry and Mulhall (2006).
novel technology into the science curricula? and the sub question, how, if at all, do teachers’ metastrategic thinking and PCK change between the summer workshop and the reflection period following the implementation of the Project NANO unit?

The three categories are:

- The influence of the summer workshop experience on the teachers’ thinking,
- Changing ideas about how to meet the very different needs of the high and low ability group classes,
- The influence of SEM on teacher thinking about how to teach science as inquiry with technology.

**Influence of the summer workshop experience on teacher’s thinking.** The teacher expressed that her initial disposition for developing the Project NANO unit was based upon a lack of preconceptions of nanoscale science and how to appropriately integrate these particular novel concepts and technologies into the eighth grade curriculum. The researcher and co-instructors noted that Annie was at a disadvantage at the beginning of the workshop because she hadn’t done the reading or watched the informational video pre-requisite assignments. In other words, she missed the opportunity to activate her metastrategic thinking and PCK by deeply reflecting on pedagogical implications of nanoscale concepts and technology in preparation for designing a unit of instruction. Thus, unlike the 22 other participants in the study, she did not begin relating new ideas with her existing PCK until she actually arrived in the summer workshop and heard the ideas of the other teachers.
The quick-paced nature of the seven-hour per day summer workshop was such that teacher participants were asked to choose the general topic of their unit prior to the beginning of the workshop, select three to eight learning objectives for the unit by the beginning of the second day of the workshop and to test their science inquiry design concepts by the end of the third day of class. To negotiate the process of making choices in a timely manner without adequate background knowledge, Annie became dependent on members of the group she chose to work with who told her that they did have a clear sense of how to approach this challenge. She allowed her lab partners to largely define the type of unit (comparison and categorization) and the mode of scientific inquiry selected for the unit, which was entirely more directive than she generally prefers to be as a teacher. Scheduling the SEM also strongly influenced her choice of what to teach and how well she considered the Project NANO unit to fit within the sequence of the greater lesson cycle.

Changing ideas about how to meet the very different needs of the high and low ability group classes. Five patterns emerged that all relate to the category to do with changes in the teacher's thinking about how to meet the needs of both high and low ability level learners and how to teach science as inquiry with the SEM and informs the sub question; how, if at all, do teachers metastrategic thinking and PCK change between the summer workshop and the reflection period following the implementation of the Project NANO unit?

Annie repeatedly emphasized barriers and limitations that influenced the unit design and success. For example, in her call-outs and interview she cited multiple pieces
of evidence that informed her realization that the unit was particularly mismatched for the needs of her so-called lower ability students. One of the things she said during the interview that she would change is to prepare adult volunteers in advance so that they could monitor the SEM while she circulates and support students, especially high needs students who she thinks need more one-on-one adult attention. During the interview she strongly suggested that Project NANO train a group of adults to support students on the SEM. She said that whatever she does, she needs to change the unit to afford her the freedom be able to move around the room to implement differentiation strategies to suit the very different needs of the high and low ability group classes.

**The influence of SEM on Annie’s thinking.** Annie reported in her CoRe that since she anticipated that she would be “stuck at the SEM” she wrote the unit to involve activities that provide for students to be self-directed to read and figure out the instructions and conceptual links to the big ideas with only the written instructions and worksheets for guidance. Annie related during her interview that in her attempt to “manage and control everyone while I was stuck at the SEM”, she designed a highly proscriptive unit that also involved some self-directed activities, possibly too many for the developmental stages of her students. Her current unit design is directive in that students must step through specific scientific procedures in a particular order; examine samples to explore questions determined by the teacher and fill-in-the-blanks on student worksheets using consistent actions and terminology. She repeatedly related during classroom observations, in her call-outs and during the interview that this is not her usual way of teaching science as inquiry and that she felt very uncomfortable with this structure
that does not lend itself to significant adaptability during the lessons but only allows for changes to be made between class days which adds a lot of work for the teacher and she thought doesn’t necessarily supports her ability to respond to students’ needs on time.

Interestingly, Annie expressed that she was really surprised that regardless of how students responded to the unit academically, every single student who responded to an informal survey she gave at the end of the unit said that they were excited about what they learned and recommended that each subsequent class have a similar learning opportunity provided to them. She relates that she had been so disappointed by the work they did in the work packets, demonstrating “horrible, horrible rudimentary lab skills, well actually, no lab skills” that she was shocked to find that every single student said that they were engaged and felt they had learned a great deal from the unit.

Annie said that what she learned from this set of survey responses is that she needs to figure out how to change the unit to engage the kids in the aspect of the unit they loved which was learning how the instruments work and debating ideas related to the observations. She realized that although they were given multiple opportunities to write or draw their observations, there were few opportunities to share their ideas with peers and actually debate ideas. So although she is certainly in no way committing to refining this particular unit and teaching a Project NANO unit again, she did describe how she will apply her new PCK to redesign other units involving technology that she is more comfortable teaching and working with in an eighth grade classroom.

For example, Annie demonstrated during the classroom observations that she learned new techniques for working with students to capture photo micrographs and
images of hand-samples and then use software to refine and compare images of the same sample at multiple scales. She said during her interview that she now plans to develop a summative activity for another technology-related unit that involves displays of students’ poster-sized images of various samples, imaged at comparable scales. She plans to engage the students in discussions about the characteristics of the samples used to categorize materials. Annie described this activity as being one that requires students to draw upon multiple forms of data used to inform problem-solving, integrate ideas from various experiences using critical thinking skills and use argumentation skills to justify claims using evidence. She sees this as an important learning opportunity for her current classes since it was apparent to her that most of the students failed to recognize the potential of quantitative means for analyzing materials using the microscopes, focusing almost entirely on the qualitative descriptive aspect of the experience. Thus, in comparison to PowerPoint presentations that she said during the interview take a long time to present information at the understanding level, a gallery-walk and discussion format takes less time and potentially elicits students’ higher order thinking skills such as critical thinking that facilitates deeper integration of knowledge and skills.

Annie explained in her interview that during the Project NANO unit, a large percentage of the time was spent figuring out how to properly prepare samples and use the instruments. In fact, due to the pressure students felt to capture usable images for their group report and presentation, she said that they didn’t really have time to explore what they saw in the samples and speculate on how characteristics may be useful for categorizing matter, a key learning goal for the unit. She worried that, “student don’t
really have a good sense of how the activities relate to the learning targets, so I need to figure out ways to more explicitly help students to make those connections without resorting to direct instruction to save time.” She “edges away from direct instruction” mainly because she believes that when students are passive learners, they absorb a limited amount of information, so her goal is to switch activities to more facilitate more active modes of learning.

Annie said her call-outs and in the interview that she now thinks that students will benefit from the opportunity to step back from the technology a bit and look at images together as a group. She shared her idea that “gently facilitated group discussions may lead to thinking about how things are shaped and how the function of that shape may possibly afford a biological advantage and give us clues as to how something can be categorized.”

**Summary of Annie’s Case**

Annie’s case is significant for a number of reasons. Although she is firm that she is not interested in teaching the Project NANO unit she designed again without making significant changes, if at all, she did reflect on her experience, identified a number of factors that contribute to a less-than-successful academic experience and solved several problems that will enable her to improve upon her approach to integrating other novel concepts and technologies into her classroom.

For example, she solved several technical issues related to the learning how to use the microscopes and teach others how to use the microscopes and facilitate students. She recognized that a large source of her discomfort with the unit was based upon the design
that forced her to stay with the SEM, which left the rest of the class essentially on their own to figure out the lab activities. Annie decided that this combination of highly prescriptive activities with under-prepared adult support is not effective, particularly for what she referred to in the interview as "low ability level students with emerging laboratory skills".

And finally, this experience contributed to the development of her PCK in that she recognized that the way in which the assignments elicited only lower order thinking such as remembering and reciting information. In response to her own thinking, she shared during the interview and in her call-outs that she is redesigning future units to incorporate lessons that teach quantitative reasoning skills with optical tools, which is a shift in practice since she says that she doesn’t normally use microscopes or hand-lenses to teach earth science concepts. She is also redesigning summative assignments that provide student with structured experiences to present both quantitative and qualitative data and defend their observations that inform how they would categorize materials. She drew upon her existing body of knowledge to push past her frustration with the unit to recognize opportunities for growth and change in her practice. To do this, she employed metastrategic thinking to figure out what went wrong, what worked well and then employed her PCK to select solutions that she feels are likely to improve upon the learning experience for everyone in the classroom.
APPENDIX D

CASE-BY-CASE STUDY OF FOUR TEACHER PARTICIPANTS: MELISSA
Melissa

Melissa is a second-year, high school biology and chemistry teacher who began teaching at a private, urban secondary school in the fall of 2012. According to her pre-survey responses, she has three-years of prior experience working with a Phenom SEM in her capacity as a college-level teaching assistant and research assistant as a student. She has taken over ten college level science courses. Prior to returning to school to become a teacher, she briefly worked as a professional biochemist. However she did not have the opportunity to teach with digital scientific instruments in her first year of teaching in a large, suburban high school last year.

In her first year, Melissa taught in the classroom next door to one of the Project NANO co-instructors. This colleague became her Project NANO instructional coach during the 2012-2013 academic year. During her one-hour, one-on-one interview she mentioned that she frequently visited her colleagues’ classroom during the 2011-2012 academic year to observe his chemistry classes. She was inspired by what she saw in that Project NANO chemistry unit and decided to become involved with the program. Her coach shared that she requested access to the project website sixth months before the summer workshop so that she could read and think about how to leverage nanoscale concepts and technology to enhance both the biology and chemistry curriculum.

After reviewing the materials, Melissa said during a classroom observation and in her interview that she concluded that she could easily see opportunities to integrate the SEM into chemistry and biology classes. Drawing on her deep content knowledge and her emerging understanding of how people learn particular topics, her PCK, she
developed two ideas for a high school biology unit months prior to the beginning of the summer workshop. She said during the summer that she entered the summer workshop with two potential units. She had each unit roughly developed including two sets of big ideas and major learning objectives identified for each unit and a selection of samples she collected and prepared in anticipation of needing to test how well each of the materials imaged with the SEM and Leica.

Melissa developed a very well-conceived diatoms unit during the summer workshop. Soon after the workshop, she was hired at a small private school, where she realized that she would have the same group of twenty-four, freshman students for four years of science and the incoming sophomores for the next three years. She said that she suddenly envisioned that the diatom unit she developed in the summer workshop would be most appropriate for the Biochemistry class she’ll teach with the current freshman the year after next in 2015.

Realizing that this revelation meant that she then needed to quickly design two new units, she contacted her Project NANO coach who met with her repeatedly to design a new biology unit in the fall of 2012. Her coach said that he also offered a percent of a composition unit for her chemistry class as one that scaffolds well with the biology unit she designed. Melissa shared during a classroom observation that she decided to adapt her coach’s chemistry unit and involve both her chemistry and biology classes in the program this year and thus, take full advantage of using the SEM as much as possible while it was at her school.
The following are the two, revised units of instruction submitted by Melissa, beginning with a biology unit of instruction:

**Project Nanoscience and Nanotechnology Outreach Unit-plans**

**Unit Title:** Utilizing diatoms as an indicator of water quality in a lentic aquatic environment

**Unit:** Ecological Interactions

**Class:** Biology, 9th grade

**Overview & Purpose:**

- Students will investigate the functional role of diatoms in a freshwater aquatic ecosystem, and be able to describe why diatoms are categorized as primary producers.

- Students will compare and contrast two key ecological concepts, habitat and niche.

- Students will engage in kinesthetic activities, from a field trip to microscope use (SEM and OLM) and predict the relative diversity/abundance of diatoms based on stream/river conditions (presence of pollutants, drainage pipes, garbage, location) and abiotic parameters (pH, dissolved oxygen, turbidity).

- Students will utilize the scanning electron microscope to image, evaluate, and analyze diatoms samples from local water sources.

**Essential Question:** What will our world look like in 100 years?

**Objectives:**

Students will be able to describe how an organism’s habitat differs from its niche, and utilize microscopy to understand how diatom abundance is correlated with stream health.

**State Science Standards:**

[High School Life Science H.2.L.2. Explain how ecosystems change in response to disturbances and interactions. Analyze the relationships among biotic and abiotic factors in ecosystems.]

**Safety Concerns:** Students will follow the guidelines for SEM sample preparation and microscope operation. Students will not load and remove samples from the cup. Instructor will conduct all loading and removal of samples, and place cup in a safe place when not in use.
Differentiation Strategies:

IEP Accommodations:

• Students will work collaboratively in groups of four for this lab activity. Students should work at their own pace, and ask questions of their lab team and the instructor.

• Instructor will model lab procedure and provide verbal explanation, visual cues, and video to build students’ conceptual understanding of SEM protocol and functioning.

• Instructor will present background information in the form of PowerPoint slides as pre-lab preparation to SEM use.

• Scaffolding will be provided during the lab to help students follow the step-by-step instructions, and whole class discussion at the end of lab will represent meaningful closure to reiterate key ideas from the SEM instruction.

• Instructor will provide oral prompt and allow select students to complete exit ticket orally or with bullet points.

ELL Learners:

• Instructor will help students build background information about ecological concepts by specifically referencing material learned previously.

• Students will participate in the creation of a word wall for the ecology unit, and add words to the list of essential terms each class period.

• Students will practice writing, drawing, and explaining ecological concepts independently and with a partner.

• Guided written practice in the form of “everybody writes brainstorm” and the end of the lesson exit-ticket will help ELL learners articulate and synthesize key concepts in ecology.

• Additional materials, such as video clips, cartoon notes, and a kinesthetic laboratory, allow students to experience multiple learning styles.

TAG Accommodations:

• All students will be encouraged to incorporate 3-5 scientific vocabulary words (given on the slide) into their exit ticket writing assignments. This task requires greater critical thinking and challenges students to integrate multiple science concepts to demonstrate a more unified understanding. Students may also include their own thinking questions in their exit ticket to demonstrate their ability to use questioning in scientific writing.
• Students could utilize complete sentences for their diatom lab report, and increase the depth and clarity of their explanations by writing more expansive answers (3-4 sentences per question).

• Students could utilize a dichotomous key or field guide to identify diatoms at the species or genus level.

• Students could count diatoms and compute various indices of species abundance/diversity by circling similar diatoms with overhead pen on laminated SEM images.

Knowledge:

<table>
<thead>
<tr>
<th>Knowledge Outcomes</th>
<th>Linked Standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>Students will be able to explain that…</td>
<td></td>
</tr>
<tr>
<td>• Diatoms are a type of algae that are ubiquitous in freshwater bodies of water. They are abundant and easy to study. Diatom species diversity is correlated with stream health. (Poulickova, Duchoslav, &amp; Dokulil, 2002)</td>
<td></td>
</tr>
<tr>
<td>• Primary producers, such as diatoms, are impacted by industrial and domestic effluents (pollution) given their sensitivity to changes in the chemical and physical environment. (Douglas &amp; Drakulic, 2002)</td>
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</tr>
<tr>
<td>• Diatoms are used as a bioindicator to determine the environmental health of bodies of water. Diatoms are sensitive to changes in salinity, pH, metals, and turbidity. (Douglas &amp; Drakulic, 2002)</td>
<td>Interaction and Change:</td>
</tr>
<tr>
<td>• Humans impact aquatic ecosystems with effluents such as fertilizers/pesticides, human waste, and industrial pollutants.</td>
<td>• H.2L.2. Explain how ecosystems change in response to disturbances and interactions.</td>
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<td></td>
<td>• H.2E.4. Evaluate the impact of human activities on environmental quality and the sustainability of Earth systems.</td>
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### Skills:

<table>
<thead>
<tr>
<th>Skill Outcomes</th>
<th>Linked Standard</th>
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<tbody>
<tr>
<td><em>Students will utilize the following science process skills and develop habits of mind…</em></td>
<td></td>
</tr>
<tr>
<td>• <strong>Measurement</strong>: Understand appropriate units to use depending on sample size, convert numbers into scientific notation, identify significant figures, use measurement tool on SEM to indicate quantitative data.</td>
<td><strong>Scientific Inquiry</strong></td>
</tr>
<tr>
<td>• <strong>Verbal explanation of procedural steps</strong>: Use sequential signal words (first, second, next, then, finally) to clearly describe the process of preparing, visualizing, and analyzing images using the scanning electron microscope.</td>
<td>H.3S.2. Design and conduct a controlled experiment, field study, or other investigation to make systematic observations about the natural world.</td>
</tr>
<tr>
<td>• <strong>Oral justification of hypothesis</strong>: Use scientific evidence to defend hypothesis, results, and to support data analysis. Verbalize a formal scientific conclusion by integrating data, analysis, and previous research on topic.</td>
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</tr>
<tr>
<td>• <strong>Controlling Variables</strong>: Identify independent and dependent variables in experiment.</td>
<td></td>
</tr>
<tr>
<td>• <strong>Critical thinking</strong>: Ask open-ended questions, use sequential steps to make conclusions, find creative and scientific explanations from peer discussions, instructional conversations, and research efforts.</td>
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</table>

### Experiences:

<table>
<thead>
<tr>
<th>Experience Outcomes</th>
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<tbody>
<tr>
<td><em>Students will be immersed in the following experiences within the unit…</em></td>
</tr>
<tr>
<td>• <strong>Eagle web cam observations coupled with biomagnification reading</strong>: Students will use digital media to observe a tertiary level consumer in an aquatic environment (eagles). Emphasis on biomagnification, how chemicals build-up in a food web, impacting organism health and survival.</td>
</tr>
<tr>
<td>• <strong>Building a food web activity</strong>: Students will work cooperatively to organize a series of</td>
</tr>
</tbody>
</table>
laminated images of organisms into a food chain and food web. Students will have labels that they need to move to the correct trophic level and identify modes of nutrition (consumer, producer, carnivore). String can be used to connect organisms and describe feeding relationships.

- **Writing a letter to hydrologist:** Students will respond to the prompts, “*How does a healthy watershed impact your life? How do your activities influence stream/river health?*”, in the form of a letter to a hydrologist. This project provides an authentic connection to the scientific community, as student letters will be sent to a stream biologist.

- **Field Trip to pond/stream:** Through a partnership with a local watershed council, students will utilize kits to explore abiotic parameters of stream health (pH, salinity, dissolved oxygen, turbidity, chemical concentrations). Students will keep a field notebook to document observations, sketches, and data.

**Assessments:**

<table>
<thead>
<tr>
<th>Assessment Strategies</th>
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<tbody>
<tr>
<td><strong>Students will complete the following as evidence of learning...</strong></td>
</tr>
<tr>
<td><strong>Pre-test, Post-test:</strong></td>
</tr>
<tr>
<td><strong>Class brainstorm:</strong> Students will complete written brainstorm of how humans impact our watershed. Responses will be shared out with class to build upon background knowledge.</td>
</tr>
<tr>
<td><strong>Ecology quiz:</strong> As a formative assessment, students will complete a quiz about diatom habitat, niche, trophic level, and how humans are influencing local watersheds.</td>
</tr>
<tr>
<td><strong>Diatom lab report:</strong> This is an individual effort. Some scaffolding will be provided in the form of headings, prompts, and sentence starters.</td>
</tr>
<tr>
<td><strong>Diatom presentation:</strong> As a group of four, students will create a digital presentation to discuss results and display SEM images.</td>
</tr>
<tr>
<td><strong>Exit ticket:</strong> The exit ticket closure activity represents a valuable formative assessment strategy for an instructor, while allowing students to demonstrate their understanding of bioindicators through a multimodal exercise (writing and drawing).</td>
</tr>
</tbody>
</table>
Works Cited


MIRACLE. Microfossil image recovery and circulation for learning and education. (2012). Diatoms. JISC.


Stations for Diatom Diversity Unit:
L.G. stands for learning goal, identified for each station task

1. Scanning Electron Microscope

   Student groups will have two sessions to utilize the SEM. As a class, students will receive training in how to take images and manipulate these pictures using the touch screen. Students will be instructed to bring a flash drive with them for image storage.

   L.G. Students will demonstrate successful use of the SEM for image creation, analysis, and measurement.

2. Light microscope to image pond scum, sketches

   Student groups will learn the procedure for operating an optical light microscope. Students may create wet mount or dry slides to examine pond scum samples for the presence of invertebrates, algae, and detritus. Students will create sketches to document their work, and include a title, labels, and color in their sketch. Observations will be documented in writing, and recorded in the lab notebook.

   L.G. Students will practice observational skills through writing and drawing. Students will operate the optical light microscope by following step-by-step procedural instructions.

3. Build a food web activity

   Students will engage in a cooperative, kinesthetic and verbal activity where they must organize a series of images of organisms into a food chain and food web. Students will organize labels for trophic levels and feeding type to describe feeding relationships in an ecosystem.
L.G. Students will be able to identify the trophic levels for a variety of organisms (primary producer, primary consumer, secondary consumer, tertiary consumer, quaternary consumer, decomposer) and explain the 10% rule of energy transfer.

4. What are diatoms? Reading, Q’s, & field guide

Students will develop scientific literacy skills by reading a short article describing diatom life history and importance in aquatic ecosystems. Comprehension questions will ask students to summarize, paraphrase, and reflect on information presented in the reading. Students will have access to field guides and a dichotomous key if they choose to identify diatoms at the species level.

L.G. Students will practice scientific literacy skills of summarizing, skimming, identifying important information, and paraphrasing information.

5. Powers of 10 scale activity

Student pairs will use computers to complete a web activity, “Powers of 10: Scale of the Universe,” to explore scale, units, and relative size of objects in our universe.

L.G. Students will be able to decide what units to use to measure an object.

6. Biomagnification article, eagle nest web cam

Students will read an article describing the impact of pesticide exposure on an aquatic freshwater ecosystem at each trophic level. Questions related to energy transfer will require mathematical calculations and analysis. Students will make qualitative and quantitative observations while watching an eagle nest web cam to better understand the behavior of a tertiary consumer.

L.G. Students will be able to define biomagnification and explain how it influences organisms at each trophic level in an aquatic ecosystem.

7. Image J: picture analysis

Students will utilize the computer program Image J for image enhancement, and measurement tools. Altering contrast, brightness, image size, and coloration can improve image resolution.

L.G. Students will become proficient in utilizing Image J software to analyze their SEM images. Instruction protocol will be given out to specific image alteration tasks.

8. Watersheds impact: letter to hydrologist

Students will write a letter describing how watershed health is linked to their everyday lives. Students will focus on the local watersheds around the Portland area, and may do research to discuss a specific locale or issue impacting watershed health. Students should pose questions to the hydrologist, and utilize content knowledge and key vocabulary in their letter.

L.G. Develop scientific literacy skills by writing a clear, concise letter using 10 ecological vocabulary words.
Group Roles for SEM Station

1. **Recorder:** In a lab notebook, the recorder will write down all observations, questions, and statements shared by the research group during their time using the SEM. The recorder must read back the observation to clarify its wording, and the group must “okay” the observation before it is recorded. It is the recorder’s job to notify the instructor when the team is finished imaging the sample at the SEM station.

2. **SEM Operator: Magnification of images:** The SEM operator is in charge of the rotary knob to adjust image magnification. This task will also involve adding labels to images, and measurement lines in the archives setting of SEM.

3. **SEM Photographer: Camera button:** The SEM camera operator is in charge of pressing the camera button to capture images from the SEM. Images should be captured at the navigational light screen and the scanning electron microscope screen.

4. **Organization/Time Keeper:** This student will keep time for the group (20 min. sessions), and guide the group through each procedural step on the chart by SEM. The student will use a dry erase marker to check off each box on the procedure chart to ensure proper protocols are being followed.

*All group members are responsible for full participation at the SEM station, including observations, questions, and hypotheses, recording details in the lab notebook, and sharing images on flash drives after the culmination of the SEM session.*

**Unit Calendar (courses at are 80 minutes long)**

- Day 1: Introduction to SEM (How does an SEM work?), Stations 1-5
- Day 2: SEM session 2, Stations 6-10
- Day 3: Data analysis from images, presentation work time
- Day 4: Student-led presentations
Melissa’s Chemistry Unit Plan:
Investigating the Percent Composition of a Heterogeneous Mixture at the Nanoscale

Unit: Nature of
Matter

Class:
Chemistry, 10\textsuperscript{th} grade

School: Small, private secondary level, urban school

Overview & Purpose:
• Students will compute the percent composition of components in a heterogeneous mixture, and be able to describe how these values compare to the actual reported mixture composition (based on ingredient mass per serving size for food items).
• Students will visually identify the various components in a mixture based on morphological and structural features (size, shape, texture, pattern).
• Students will engage in inquiry by developing an experimental technique to accurately calculate percent composition of a mixture (repeated trials, standardization, size of sample images), and work collaboratively in research teams to present their findings at a formal symposium.
• Students will utilize the scanning electron microscope and Leica microscope to image, evaluate, and analyze household mixture samples (tea, spice mix, Kool-Aid, and coffee).

Essential Question: How can matter be described, measured, and categorized?

Objectives:
Students will be able to describe how the distribution pattern of components in a mixture determines mixture type (homogeneous vs. heterogeneous), and utilize microscopy to understand how to visually and mathematically determine the percent composition of a household mixture.

Oregon State Science Standards:
High School Science H.1. Structure & Function: A system’s characteristics, form, and function are attributed to the quantity, type, and nature of its components. This Oregon state science standard relates to the unit goal of describing how chemical and physical properties of substances change based on scale (size-dependent properties).

High School Science H.3. Scientific Inquiry: Based on observation and science principles, formulate a question or hypothesis that can be investigated through the collection and analysis of relevant information. This Oregon state science standard
relates to the unit goal of guiding students through the process of inquiry, hypothesis testing, and learning the steps of the scientific method by completing a formal lab write-up. The emphasis in this unit is collaborative exploration, creative thinking, and group problem solving. To design a successful technique to compute percent composition of an unknown mixture, students must develop skill sets that span mathematical and chemical disciplines, with an emphasis on visual discovery and photographic analysis.

Safety Concerns:
Students will follow the guidelines for SEM sample preparation and microscope operation. Students will not load and remove samples from the cup. Instructor will conduct all loading and removal of samples, and place cup in a safe place when not in direct use. It is imperative the students follow all instructions for microscope utilization, and ask questions to confirm proper sample preparation. Instructor will oversee SEM station, with the expectation that student groups work independently at all other stations.

Differentiation Strategies:

- Students will work collaboratively in groups of four. Each student should work at his/her own pace, and ask questions of the lab team and instructor for additional clarification.

- Instructor will model lab procedure and provide verbal explanation, visual cues, and video to build students’ conceptual understanding of SEM protocol and operation.

- Instructor will present background information in the form of PowerPoint slides as pre-lab preparation.

- Scaffolding in the form of a guided notes sheet, think-pair share, and video footage will help students contextualize nanotechnology curriculum. In addition, exit ticket reflection and whole class discussion of project represent meaningful closure to reiterate key ideas about nanoscale science.

- Instructor will help students build background information about mixtures and nanotechnology by specifically referencing material learned previously during the nature of matter unit.

- Students will practice writing, drawing, and explaining mixture and nanotechnology concepts independently in the formal lab-report, and with a partner informally during think-pair-share activities.
• Additional materials, such as video clips, guided notes, and an emphasis on kinesthetic exploration, will allow students to learn by activating multiple learning styles (kinesthetic, visual, linguistic, and spatial).

• All students will be encouraged to incorporate 3-5 scientific vocabulary words (given on the slide) into their exit ticket reflections. This task requires greater critical thinking and challenges students to integrate multiple chemical concepts to demonstrate a more unified understanding. Students may also include their own questions in the exit ticket to demonstrate further engagement with the material.

• Students will be encouraged to utilize formal language, chemical terminology, and illustrations to communicate their understanding of the percent composition of a mixture in the formal lab-report.

• To emphasize scientific literacy, instructor will promote written comprehension of key unit goals by asking students to write more expansive answers (3-4 sentences per question) for the lab report sections.

• Students could count mixture components by adding a digital grid overlay in Graphic Converter or Image J, or by circling similar mixture components with an overhead pen on laminated SEM images.
Knowledge:

<table>
<thead>
<tr>
<th>Knowledge Outcomes</th>
<th>Linked Standards</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Students will be able to explain that...</em></td>
<td>NWA Chemistry Proficiency: Fall 2012: classify matter in terms of physical and chemical properties, phase and type; differentiate between pure substances and mixtures</td>
</tr>
<tr>
<td>• Nanoscale science is an interdisciplinary science involving chemistry, physics, biology, engineering, and computer science. It involves examining and manipulating objects at the atomic, molecular, and macromolecular scale. 1 nanometer = 1 billionth of a meter.</td>
<td></td>
</tr>
<tr>
<td>• Nanotechnology may have applications to enhance health care (chemical and biological sensors, drugs and delivery devices, prosthetics and biosensors), technology (better data storage and computation), and the quality of our environment (clean air, clean energy with Nano solar cells).</td>
<td></td>
</tr>
<tr>
<td>• Scale changes everything. At the nanoscale, chemical and physical properties of elements change as electromagnetic forces dominate (gravitational forces become negligible). Quantum mechanics can be utilized to describe motion and energy. At the nanoscale, a larger surface area to volume ratio exists, resulting in greater bonding and reactivity at the atomic level. Random molecular motion becomes an important force to explain particle movement.</td>
<td></td>
</tr>
<tr>
<td>• Mixtures consist of two or more elements/compounds that are physically combined, but not chemically combined. Mixture components often exhibit chemical and physical properties unique to the component. In contrast, a compound consists of atoms of two or more elements that are chemically combined, and the properties of the compound are distinct from the properties of its individual components.</td>
<td></td>
</tr>
</tbody>
</table>
**Skills:**

<table>
<thead>
<tr>
<th>Skill Outcomes</th>
<th>Linked Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Students will utilize the following science process skills and develop habits of mind...</td>
<td><strong>Oregon State Science Standard:</strong></td>
</tr>
<tr>
<td>• <strong>Measurement:</strong> Understand appropriate units to use depending on sample size, convert numbers into scientific notation, identify significant figures, use measurement tool on SEM to collect quantitative data.</td>
<td><strong>Scientific Inquiry H.3S.2.</strong></td>
</tr>
<tr>
<td>• <strong>Verbal explanation of procedural steps:</strong> Use sequential signal words (first, second, next, then, finally) to clearly describe the process of preparing, visualizing, and analyzing images using the scanning electron microscope.</td>
<td>Design and conduct a controlled experiment, field study, or other investigation to make systematic observations about the natural world.</td>
</tr>
<tr>
<td>• <strong>Oral justification of hypothesis:</strong> Use scientific evidence to defend hypothesis, results, and to support data analysis. Verbalize a formal scientific conclusion by integrating data, analysis, and previous research.</td>
<td></td>
</tr>
</tbody>
</table>

**Experiences:**

**Experience Outcomes**

Students will be immersed in the following experiences within the unit...

- **Prom 2045 Reading & Questions:** Students will read a story about prom set in 2045. Emphasis is on applications and current developments of nanotechnology (cell phone implant in ear, car with solar paint, dress with quantum dot pattern). Class discussion of current and future applications will allow students to process new information and share science-related questions about nanoscale science.

- **Mixture, Compound, or Element Lab:** Students will work cooperatively to organize a series of household objects into the categories of mixture, compound, or element. Students will complete pre-lab questions about types of matter, and should justify their pick of mixture, compound or element based on physical and chemical properties.

- **Introduction to Nanoscale Science Video:** Students will watch a short video describing the field of nanotechnology and future applications.
**Assessments:**

Assessment Strategies

*Students will complete the following as evidence of learning...*

- **Percent Composition of a Mixture Lab Report:** This is an individual effort. Some scaffolding will be provided in the form of headings, prompts, and sentence starters.
- **Research presentation:** As a group of four, students will create a digital presentation to discuss results and display SEM images.
- **Exit Ticket Reflection:** The exit ticket closure activity represents a valuable formative assessment strategy for an instructor, while allowing students to demonstrate their understanding of nanoscale science through a multimodal exercise (writing and drawing).

**Stations for Percent Composition of a Mixture Unit:**

L.G. stands for learning goal, identified for each station task

1. **Scanning Electron Microscope**

   *Student groups will have two sessions to utilize the SEM. As a class, students will receive training in how to take images and manipulate these pictures using the touch screen. Students will be instructed to bring a flash drive with them for image storage.*

   L.G. Students will demonstrate successful use of SEM for image analysis and measurement.

2. **Light microscope to image mixture components**

   *Student groups will learn the procedure for operating an optical light microscope (Leica). Students may create wet mount or dry slides to examine mixture samples for images of larger sample areas. Students will create sketches to document their work, and include a title, labels, and color in their sketch. Observations will be documented in writing, and recorded in the lab report.*

   L.G. Students will practice observational skills through writing and drawing. Students will operate the optical light microscope by following written step-by-step procedural instructions.

3. **Powers of 10 scale activity**

   *Student groups will use computers to complete a web activity, “Powers of 10: Scale of the Universe,” to explore scale, units, and the relative size of objects in our universe.*
L.G. Students will be able to decide the appropriate range of units to measure objects.

4. **Image J: picture analysis**  
   *Students will utilize the computer program Image J for image enhancement and measurement tools. Altering contrast, brightness, image size, and coloration can improve image resolution.*

L.G. Students will become proficient in utilizing Image J software to analyze their SEM images. Instruction protocol will be given out to promote specific image alteration tasks.

**Group Roles for SEM Station**

1. **Recorder:** In a lab notebook, the recorder will write down all observations, questions, and statements shared by the research group during their time using the SEM. The recorder must read back the observation to clarify its wording, and the group must “okay” the observation before it is recorded. It is the recorder’s job to notify the instructor when the team is finished imaging the sample at the SEM station.

2. **SEM Operator: Magnification of images:** The SEM operator is in charge of the rotary knob to adjust image magnification. This task will also involve adding labels to images, and measurement lines in the archives setting of SEM.

3. **SEM Photographer: Camera button:** The SEM camera operator is in charge of pressing the camera button to capture images from the SEM. Images should be captured at the navigational light screen and the scanning electron microscope screen.

4. **Organization/Time Keeper:** This student will keep time for the group (15-20 min. sessions), and guide the group through each procedural step on the chart for proper functioning of the SEM.

*All group members are responsible for full participation at the SEM station, including observations, questions, and hypotheses, recording details in the lab report, and sharing images on flash drives after the culmination of the SEM session.*
Unit Calendar (courses at my school are 80 minutes long)

- **Day 1: Tuesday, Nov. 20th**: Introduction to Nanotechnology notes, Sample preparation, start background information (Page 1 of lab report)

- **Day 2: Tuesday, Nov. 27th**: Nanotechnology applications notes, Stations 1-4, Exit ticket reflection

- **Day 3: Thursday, Nov. 28th**: Size-dependent properties notes, Stations 1-4, Presentation prep

- **Day 4: Friday, Nov. 29th**: Student-led presentations, Organize photo contest and guess the image slides for Dec. 7th lunch event at NWA.
**Melissa's Unit of Instruction**

Melissa listed as the following unit objectives; “Students will be able to describe how the distribution pattern of components in a mixture determines mixture type (homogeneous vs. heterogeneous), and utilize microscopy to understand how to visually and mathematically determine the percent composition of a household mixture.”

Melissa wrote on her unit plan, “this Oregon state science standard relates to the unit goal of guiding students through the process of inquiry, hypothesis testing, and learning the steps of the scientific method by completing a formal lab write-up. The emphasis in this unit is collaborative exploration, creative thinking, and group problem solving. To design a successful technique to compute percent composition of an unknown mixture, students must develop skill sets that span mathematical and chemical disciplines, with an emphasis on visual discovery and photographic analysis.”

**Melissa’s Knowledge, Skills, Experience, Community and Assessment scores.**

Melissa’s sophomore chemistry unit of instruction scored sixty-three of sixty-five possible points on the KSECA scoring guide, earning one of the highest scores in the group of 23 participants in the study and in the entire group of teachers who participated in the three summer Project NANO workshops. Melissa explained during her interview that she worked very closely with her coach and the scoring guide to ensure that she thoroughly addressed each of the curriculum elements on the planning template. She shared that because she is currently in the early induction phase of her career, she is experiencing intense mentoring from multiple veteran teachers, so she is often asked to articulate her reasoning and justify instructional choices, and thus she feels she has
developed the habit of publically examining and improving upon her PCK. She repeatedly emphasized how greatly she appreciated the unit of instruction template as a planning tool used to facilitate collaborative planning discussions and reflection.

Recall that the unit of instruction scoring guide areas of assessment are *knowledge and concepts*, *science inquiry and engineering design skills*, *student experiences*, *learning community* and *assessment of student achievement*. Melissa’s unit scored 15 of 15 points on the *knowledge and concepts* element because she specifically listed state content standards and major learning objectives in clear, student-friendly language and introduced new, grade-appropriate concepts with clear links to prior knowledge. The unit scored 15 of 15 points on the *science inquiry and engineering design skills* because the unit asked students to participate in a complete inquiry cycle. They were asked to generate testable questions, identify variables, develop an inquiry design and data collection protocol, employ appropriate technology in their study and critically evaluate their empirical data results including error analysis, present and defend knowledge claims.

The unit scored 11 of 12 points in the *student experiences* category. The unit involved students in exploring new concepts in the context of real-world application and facilitated the use of metacognitive strategies to identify, monitor and regulate learning. The unit describes accommodations for diverse learners; however the unit lost one point because it did not explicitly prompt students to pursue immediate additions or deeper investigations. That said, Melissa did follow-through on the idea she articulated in her
planning to open the science lab during lunch time and after school for students who wished to spend more time on their primary investigation.

Melissa’s chemistry unit scored 11 of 12 points in the *learning communities* section losing one point because although students were asked to communicate and defend their results in the form of a written report, they were only asked to present their understanding before their peers, and not to make and defend knowledge claims before their peers. Again, the *assessment of student achievement plan* was particularly strong in this unit including elements such as pre-assessments used to inform changes to the lessons and assist students with identifying misconceptions and self-assess learning. Formative assessments including exit tickets implemented mid-investigation which the teacher collected and responded to at the beginning of each class, group discussion responding to both student and teacher prompts and daily student journaling in response to written and spoken guiding questions. Each of these formative assessment activities provided multiple opportunities for the teacher to check and guide student thinking and for students to revise their thinking. Post-assessments in the form of individual reports and group presentations provided multiple forms of summative evidence of student learning.

**Melissa’s Pre and Post Survey scores.** Melissa is another example of a teacher who was not sufficiently challenged by the pre and post survey questions, thus the instrument had limited utility to actually measure her scientific content knowledge gains. Because she was involved in the first of the three workshops, she took the pre and post
survey with four open-ended questions and no multiple-choice questions. The following table A.11 presents Melissa’s pre and post survey scores:

**Table A.11**

**Melissa’s Pre and Post Survey Scores**

<table>
<thead>
<tr>
<th>Pre – Post Survey Questions</th>
<th>Pre Survey</th>
<th>Post Survey</th>
</tr>
</thead>
<tbody>
<tr>
<td>What is the difference between an optical microscope and an SEM”</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Describe 5 key components of the scanning electron microscope (the mechanics of the tool)</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Describe safety protocols related to working with secondary level students and a table top SEM</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Provide a brief description of how you might integrate optical and electron microscopes in a course to instruction students on form and function related to the discipline you teach.</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

Melissa scored all of the possible points on pre and post survey on the first question that asked for a description of the difference between the optical and electron microscope. She did however move from one to three points in the post survey on the second question that asked her to name five part of the SEM. She later said on the last day of the summer workshop that her responses on the pre and post survey measured the fact that she had been involved in situations where language was used in imprecise ways to describe the instrument and not necessarily that she did not know the function of the various parts.
Melissa also gained one point on the post survey on the third question which asks about laboratory safety by adding specific load protocols, ideas about how to supervise students around the instruments and basic lab protocol such as the use of eye goggles. Finally, because Melissa entered the workshop with not one, but two good ideas for how she might integrate nanoscale science into the curriculum she scored three of three points on both the pre and post survey.

Despite the obvious limitations of the instrument, it is interesting to note that in comparison to teachers with little to no prior conception of the nanoscale or how to teach nanoscale science concepts using an SEM, Melissa’s scores support the obvious fact there is some advantage to being a novice teacher with recent college experience working directly with nanoscale concepts and technology in a teaching and learning environment.

**Melissa’s Content Representations (CoRe), call-out and interview reflections.**

Melissa used the CoRe table differently than the rest of the participants did. Instead of listing five to eight big ideas for one, two-week unit of instruction, Melissa used the table to share her plans for three distinct unit-plans. In the cells designated as the “big ideas” cells, Melissa listed the title of a ninth grade unit, “Diatoms as a bio-indicator of stream health”, which she decided to rewrite at a later date into an eleventh grade biochemistry unit; a tenth grade chemistry unit adapted from her coaches’ unit entitled, “Examining the percent composition of a household mixture (tea, spice mix, types of salt, Kool-Aid mix, etc.), and another ninth grade biology unit entitled, “Investigating Evolutionary Relationships in the Order Mammalia through Hair Morphology”.

Here is Melissa’ CoRe table with the researcher memos:

### SEM Unit Brainstorm: Content Representations Table

<table>
<thead>
<tr>
<th>This CoRe is designed for:</th>
<th>A:</th>
<th>B:</th>
<th>C:</th>
<th>Researchers Memos</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Level 1 Biology (9th grade)</td>
<td>Level 1 Biology (9th grade)</td>
<td>Level 2 Chemistry (10th grade)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Diatoms as a bio-indicator of stream health</td>
<td>Investigating Evolutionary Relationships in the Order Mammalia through Hair Morphology</td>
<td>Examining the percent composition of a household mixture (tea, spice mix, types of salt, Kool-Aid mix, etc.)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Call-out</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Should be taught in nature of science and matter unit in the fall</td>
<td></td>
</tr>
<tr>
<td>What you intend the students to learn about this idea.</td>
<td>-Compute the percent composition of components in a heterogeneous mixture, and compare to actual reported percent composition based on ingredient mass and serving size.</td>
<td>Call-Out</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Not all mixtures</td>
<td></td>
</tr>
</tbody>
</table>

Because they were not clearly labeled, students did on-line research about the items they brought in to find if there are any standards for products such as Earl Grey tea in the industry that they could then extrapolate from. A few students then went on to look for SEM images of substances to compare with their own images of their samples to see if the industry product descriptions of the substances in the mixture match what they are seeing in their own image. Though they could not...
She is negotiating where to situate the unit most effectively beginning with the idea that it could naturally fit in various classes and with a variety of units.

<table>
<thead>
<tr>
<th>Call-out</th>
</tr>
</thead>
</table>
| Show all students measurement tool on SEM and ask them to record data  

- Develop an experimental technique to calculate percent composition of a mixture (repeated trials, standardization, necessarily positively identify the substances in the mixture, they did describe the morphological characteristics of the materials found within the mixture to categorize them based on whether or not the substance was heterogeneous or homogeneous. The teacher said that realizes the value of this approach and plans to intentionally include this comparative approach to looking at known quantities next year as a key part of the unit plan.

Students at the SEM repeatedly forgot to include measurements at comparable scales, thus the teacher needed to remind them to do this and then repeatedly demonstrate how to use the controls to take measurements. The teacher shared her ideas for why students frequently missed this step; they were so focused on capturing clear images that didn’t charge they forgot what else could be done with the SEM, they were unsure of how to switch to the measurement function and some were unsure as to how to relate the measurements to the percent composition idea. So by saying that she needs to show all students the measurement tool, she is not just saying that its more efficient to show everyone how to take a measurement at once, she is also saying that a whole-group discussion about how to do it and why to do it
<table>
<thead>
<tr>
<th>Why is it important for the students to know this?</th>
<th>Integrates mathematical and quantitative skills with basic chemical understanding of mixtures.</th>
<th>Several teachers mention the box method and the need to show students how and why to use this method prior to capturing images. This teacher recognizing a potentially helpful strategy for focusing students’ attention on characterizing a sample using a simple but powerful method.</th>
</tr>
</thead>
</table>
| What else do you know about this idea (that you do not intend the students to know yet?) | -Mixtures can be classified as homogeneous or heterogeneous, depending on the composition.  
-Show images of both types of mixtures and then use chemical examples  
-Homogeneous mixtures appear uniform in | She is addressing potential misconceptions here related to the idea of showing images of both types of mixture to clarify the idea that there is more than one type. |

Students were asked to learn new disciplinary and
| The teacher is considering a technique for increasing the degree of higher order thinking in the unit | technical language at the same time, which was challenging for some, perhaps too challenging since a lack of consistent use of language and understanding of terms impeded some group’s ability to discuss their observations and make meaning through a situated, social learning experience | composition, while heterogeneous mixtures do not appear uniform throughout. -The chemical and physical properties of elements changes based on size-dependent properties of nanoparticles (e.g. nanoscale gold vs. macroscale gold differ in color).

**Call-out**

_This was a very successful lesson, taught with PowerPoint, images and video. Students struggled to connect this content to their research projects_  

-Percent composition of an unknown mixture can be compared with the actual distribution of components to compute percent error.

**Call-out**

_We’ve learned_  

Students had difficulty connecting the big idea of size dependent properties to their own inquiry activities.  

Intentional scaffolding of concepts framed in a testable manner.

Melissa spoke about this being a nice connection for this year’s biology students to make when they get into chemistry next year. Possibly for a science fair project?
Although most of the hair samples imaged well during the summer workshop, three teachers mentioned that students had difficulty with hair charging and with seeing the scales on the strand well enough to characterize the features. Thus, perhaps hair should not be presented a sure-fire material to image using the SEM.

Learning opportunities made possible with the use of technology

- Analyzing percent composition of a mixture and identifying mixture components at the nanoscale using the SEM Phenom.

Difficulties /limitations connected with

- How to select the representative sample from which to calculate percent error – so this should build upon background knowledge. She emphasizes here how a visual method combined with a mathematical exercise may help students to conceptualize.
teaching this idea: plan her diatom unit by integrating authentic experiences working with a science professional. Informally she spoke about how this piece will potentially increase students level of engagement and encourage her biology students to learn how the professionals negotiate the task of identifying particular features on a diatom useful for keying out species.

<table>
<thead>
<tr>
<th>Common misconceptions students hold about this idea:</th>
<th>percent composition? Number of trials? Size of boxes?</th>
<th>complex ideas.</th>
</tr>
</thead>
<tbody>
<tr>
<td>-When examining the mixture of a food item, the percent composition will be identical to the listed masses for each serving size</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-Mixtures that students may have encountered (air, water, honey, yogurt) may look pure, but are really mixtures of multiple</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Call-out*

I think showing students a Power Point from last year really helped them understand the percent composition calculations better – very visual method.
substances.  

Ingredients can be identified based on shape/size at the nanoscale.

**Call-out**

*Show that many ingredients can be identified by locating SEM photos on-line and then comparing these photos to SEM images of the mixture.*

<table>
<thead>
<tr>
<th>Difficulty/limitations connected with use of scientific instruments</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>This reflection is a result of a mini-inquiry performed by the teacher related to how to prepare and mount specimens on the stub. In contrast to several of the middle-level teachers and one high school</td>
<td></td>
</tr>
</tbody>
</table>
| -Potential charging on sample  
**Call-out**

*The handout on this topic was very helpful – print copies for entire class next year.*

Difficulty discerning various mixture components or identifying the specific ingredients from list of all components.
teacher who described the time spent on sample prep to be wasted time, Melissa is deeply considering how to improve upon teaching what she knows to be one of the most critical steps of microscopy and how to most effective prepare samples for different views.)

<table>
<thead>
<tr>
<th>Knowledge about students’ thinking which influences your teaching of this idea</th>
<th>-Students need formal instruction in composition of matter (mixture, compound, substance), and should be familiar with percent error calculation as well as percent composition computation.</th>
</tr>
</thead>
</table>
| Knowledge about students’ thinking that influences how you integrate technology into the | Students can use iPhones or cameras to document light microscope images  
-Students should bring a flash drive  
-Have multiple |
<table>
<thead>
<tr>
<th>Lesson</th>
<th>Melissa found the Power of 10 video shared at the workshop to be developmentally appropriate and engaging for ninth and tenth graders, whereas middle-level teachers collaborated to find a different video to meet the needs of 6-8 grade students.</th>
<th>ways for students to interact with technology-manual, online instructions, and verbal instructions.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other factors that influence your teaching of this idea.</td>
<td>- How to image mixtures to get clearest images of individual components, as well as of mixture as a whole? - Difficulties identifying mixture components, comparing to internet images?</td>
<td></td>
</tr>
<tr>
<td>Teaching procedures (and particular reasons for using these to engage with this idea).</td>
<td>- Discuss how humans have manufactured food products by combining chemicals and ingredients. - Understand the distinction between homogeneous and</td>
<td></td>
</tr>
</tbody>
</table>
Here is evidence of the teacher continuing to plan the diatom unit by considering how to appropriately scaffold experiences with the Project NANO unit experience they had this year. At the summer workshop, Melissa discussed at length her idea of how to integrate field experiences related to water quality into her unit. A middle school teacher is now working with Melissa to further design the unit to suit the needs of Summa students and high school students. They are sharing images now as part of that online discussion heterogeneous mixtures, as well as differences in physical/chemical properties depending on scale.
Each of the units of instruction Melissa developed are three-weeks in duration, with two of those weeks involving the SEM and Leica. The two units she actually taught this year, and therefore is able to fully reflect upon for the purposes of this study are the chemistry unit on “percentage of a composition in a mixture” and the biology unit “investigating evolutionary relationships in the order Mammalia through hair morphology”. These two units were coded for patterns and categories using the same techniques applied to the interview transcript coding. Because the CoRe and call-out categories fit well within the set of categories developed from the interview transcript codes, I will integrate the report for all three data sources. In the case of the CoRe call-out reflections, I coded and developed categories for all three units. This is because the teacher is clearly thinking about how to scaffold learning between all three units and rethinking how to sequence topics and activities based on her experiences implementing two of three units this year.

Five categories and one set of sub-categories were developed from the CoRe, call-out reflections and interview transcripts. The categories and sub-categories are:
Type of unit. The biology unit is designed to compare structural difference of mammalian hair-types to learn the definition of morphology and use Linnaean taxonomy to classify samples. Students will learn the definition of morphology and Linnaean taxonomy, how to create a cladogram based on morphological data, identifying structural differences of mammalian hair, including hair type (guard, whiskers, under fur, velli, defensive spines, or fur), cross-sectional area, shape, length, color, texture, condition of the cuticle, length of keratinized scales, cuticle pattern (coronal, spinous, or imbricate). She wrote in her CoRe that it’s important for students to learn this content because these characteristics “helps us classify organisms and understand evolutionary relationships using morphology as a key indicator.”

The chemistry unit is designed to “identify the various components in a mixture based on morphological and structural features (size, shape, texture, pattern)”. [Students will] “compute the percent composition of components in a heterogeneous mixture, and compare to actual reported percent composition based on ingredient mass and serving size, identify the various components in a mixture based on morphological and structural
features (size, shape, texture, pattern), develop an experimental technique to calculate percent composition of a mixture (repeated trials, standardization, box method).” She describes this importance of this unit as being that it “integrates mathematical and quantitative skills with basic chemical understanding of mixtures.”

**Sequence and Scaffolding of the unit.** The chemistry unit was designed as a new unit “to really focus on those quantitative skills.” The biology unit was designed as an extension to a genetics unit. The units were taught concurrently with one another to take advantage of the time the SEM was in the school lab. Melissa reported in her CoRe and during her interview that the units bridged the period immediately before and after Thanksgiving break, which would have been a bigger problem at her last school where her larger classes of less engaged students often forgot critical information over holiday breaks. Although time with the SEM was cut a few days short by the holiday, Melissa found that her students had well established classroom norms having participated in laboratory groups to conduct several inquiries earlier in the academic year, thus most of the students were able to support one another to remember what they needed to know and move quickly through the units.

Most of Melissa’s call-out reflections focused on changes she plans to make to each of the units. Although frequency counts is not a tool used in the research to identify call-outs as more or less important than one another, it is interesting to note that Melissa wrote eight call-outs related to new ideas about how to scaffold the units differently. For example, Melissa wrote after the title of the chemistry unit, examining the percent composition of a household mixture (tea, spice mix, types of salt, Kool-Aid mix, etc.)
“should be taught in nature of science and matter unit in the fall.” This is an example of the teacher beginning to figure out how to optimally schedule the unit into the greater curriculum cycle. Here we saw Melissa setting up an idea that she could easily translate into a testable pedagogical question to see if students do indeed improve in their ability to conceptualize the big ideas and make connections between ideas if the unit is moved to an earlier time in the year to be part of a nature of matter unit.

Interestingly Paul, who framed his unit around the same topic, did envision this unit as part of his introduction to the nature of matter segment of the greater lesson cycle. He too made comments about how to scaffold in basic concepts earlier in the unit so that students had a better sense of how their inquiry connects to the big ideas related to identifying and categorizing materials as homogenous or heterogeneous.

In several instances, Melissa identified situations wherein students would benefit from whole class instruction to scaffold a skill or piece of knowledge earlier in the unit to enable students to more fully engage in the inquiry process. For example, she wrote, “maybe instructor could lead science students in a KWL table [discussion] or elicit misconceptions or provide these statements and have students groups identify the true or false.” This strategy is also a formative assessment the teacher could add to the unit to inform how to calibrate instruction to meet the needs of her students. Melissa also identified language and concepts to pre-teach before the lab work. For example, she wrote a call-out that said “Need to pre-teach term “morphology” and connect it to structure and function as a key theme of biology” because “by familiarizing students with language and discipline terms, project will be more successful.” Just as Paul observed,
students were asked to learn new disciplinary and technical language at the same time, which was challenging for some, perhaps too challenging since a lack of consistent use of language and understanding of terms impeded some group’s ability to discuss their observations and make meaning through a situated, social learning experience.

Melissa related examples of situations where she realized that she needed to scaffold learning with supplemental materials. For example, she wrote a call-out that said, “The student group focusing on hair types needed more information on hair structure, especially scale patterns and length.” Realizing the need mid-way through the student’ inquiry experience, she added readings to help the hair group to connect the lab activities to the big ideas of structure and function, evolution, genetics. Melissa related during her interview that as a result of this “just in time teaching”, “the hair group successfully connected topic to evolutionary similarity of humans – dogs, human - llama, and human –pig. Linking genetics, evolution and structures and function made this PowerPoint one of the most successful.” In a call-out comment, she demonstrated new PCK as she reflected that “the handout on this topic was very helpful – print copies for entire class next year.”

Melissa addresses potential student misconceptions in chemistry with the call-out comment, “show images of both types of mixtures and then use chemical examples.” Here she is talking about sequencing a lesson on types of mixtures prior to working with the microscopes. She says that helping students to relate the idea and terminology related to mixtures to something familiar may help them to contextualize the mixture concept and then apply the concept to categorize substances.
Another example of scaffolding relates to structuring activities. Melissa wrote in her unit plan “show all students measurement tool on SEM and ask them to record data”. When asked about this memo, Melissa shared that she explained each of the controls to the students as they used the SEM. Her students repeatedly forgot to include use the SEM to capture measurements at comparable scales, thus she needed to remind them to do this and then repeatedly demonstrate for each group how to use the controls to take measurements.

The teacher shared her ideas for why students frequently missed the measurement step during her interview, "They were so focused on capturing clear images that didn’t charge they forgot what else could be done with the SEM. They were unsure of how to switch to the measurement function, they failed to understand the importance of comparing images of materials at the same scale and some were unsure as to how to relate the measurements to figure out the percent composition." When asked for clarification of her meaning when she said that she needs to show all of her students in the class the measurement tool at once, she said that she was not just saying that its more efficient to show everyone as a whole group how to take a measurement, she was also saying that students may be more likely to understand how and why to use the SEM to capture both qualitative and quantitative data useful for categorizing matter.

Melissa used the CoRe template to prompt her reflections and record her call-outs with her emerging ideas about how to sequence, scaffold and organize the progression from the freshman biology course to the chemistry course to the biochemistry course. For example, she wrote in one of her call-outs “students should consider how chemical
(like dye, bleach) or heat (straightening) affects hair strand.” During the final classroom observation she informally spoke about this being a nice connection for this year’s biology students to make when they get into chemistry next year and that this could possibly turn into a great science fair project.

Evidence of Melissa’s metastrategic thinking is also found in call-outs related to where to situate the diatom unit most effectively beginning with the idea that it could naturally fit in various classes and with a variety of units. She also commented on ideas for how to structure the unit, “diatom-focus could easily be a whole class project for biology ecology or environmental science units or for chemistry in an environmental chemistry unit.” Finally, Melissa’s call-outs provide evidence for how to end the diatom unit, “in [the] future, this unit could end with a fieldtrip to wetlands for water-quality testing, or the fieldtrip and testing could occur on first day of unit to collect diatom samples for project and a talk about site history.”

Pedagogical strategies. The next category is that of pedagogical strategies which is comprised of three sub-categories developed from the chemistry and biology units: successful pedagogical strategies used in the unit, the use of assessment strategies to inform both the teachers’ and students’ thinking and differentiation strategies. I will begin with successful pedagogical strategies.

Melissa wrote in her CoRe “the chemical and physical properties of elements change based on size-dependent properties of nanoparticles (e.g. nanoscale gold verses macroscale gold differ in color). In her call-out reflection she wrote that visual tools used to teach this complex idea were very effective, “this was a very successful lesson, taught
with PowerPoint, images and video.” In another call-out she wrote, “I think showing students a PowerPoint really helped them understand the percent composition calculations better – very visual method.” In each of these call-outs she emphasized how a visual method combined with a mathematical exercise may help students to conceptualize complex ideas. She emphasized successes again when she wrote, “at stations, Power of Ten video was well received, scale of the universe simulation was good”. When asked during her interview, she said that she successfully used a Power of 10 video shown at the summer workshop which she felt to be developmentally appropriate for high school level students.

Middle school teachers did not find this to be the case, so they found an alternative video to express the ideas using more simple language. Melissa said that all of her students read at grade level and that English is their first language and that the complex use of culturally specific metaphors and language used in the video is suitable for her students. In both classes, students were assigned into lab groups by the teacher and instructed to work as a group to develop an inquiry and bring in their own selections of samples to examine with the microscopes. “In biology, each student research group chose a topic, those topics ranged from ‘is dust alive?’ or looking at the antenna structure and function between a bee and a beetle or looking at feather structure and function, talking about evolutionarily structure and function, again hair structure and function, so more broadly tying into those essential themes of biology.”

Melissa’s PCK informed two classroom management strategies she said that she successfully employed in the unit. During the interview she said that she chose the lab
groups herself because she felt that this would give her more control of group dynamics. Anticipating that once the lab rotations began, she would be with the SEM most of the time, she selected group leaders in advance and frontloaded them with technical and content knowledge necessary to facilitate their own group. Melissa then populated each group with students with the intention of balancing personalities, aptitude and dispositions. She also thought through how to organize each station within her small laboratory. She placed the sample prep and Leica station very near to the SEM so that she could toggle between assisting at each of the stations where she anticipated that the student would need the most help. She allowed students to make their own choices for where they wanted to complete the other station activities that were loaded onto laptop computers the students could move around and not disturb others when they needed to have group discussions.

**Student assessment strategies.** Next I address the category of PCK related to the use of student assessment strategies. Recall that the chemistry unit was taught as a new unit. In contrast to the biology extension unit where she skipped right from introductory genetics into exploring how mammalian hair cuticle patterns distinguish animal species, Melissa began the chemistry unit by explicitly linking nanoscience science and technology concepts as a conceptual bridge between two-distinct units. “In chemistry I pre-taught more nanotechnology, so we looked at size dependent properties and their influence on chemical and physical changes and talked more about the interdisciplinary applications of nanotechnology…saw some video, talked more about electron beam SEM functioning, what is charging…I think multi-media, so one thing that worked really well was
that I used a lot of video clips and different types of [print] resources from the narrative Prom article to some of these more engaging applications [of nanotechnology] in the new articles, that was good.”

Despite pre-teaching in chemistry prior to the arrival of the microscopes in the lab, Melissa said during a classroom observation that she noticed that chemistry students were overall more tentative about working with the microscopes and publically discussing their observations than her biology students seemed to be. She realized that the chemistry students appeared to feel more self-conscious about their nanoscale experience in part because they were afraid to use the wrong terminology or publically fail to learn to use the microscope controls correctly. Melissa wondered how much of their reticence may have to do with a developmental stage of fifteen and sixteen-year-olds navigating social interactions. She also wondered if this behavior may been due to the fact that the chemistry concepts and images they were approaching were comparatively new to the students, whereas the freshmen biology students may have had prior exposure to many of the concepts involved in the hair unit.

For example, students in biology may have previously learned to categorize specimens and probably have seen maps of genetic evolution or phylogenetic trees prior to this unit, thus they may have had some sense of the concepts of phenotypes and genotypes and ideas as to how they could use the microscopes to collect evidence to inform an inquiry. The chemistry students on the other hand were learning new concepts related to homogeneous and heterogeneous mixtures, solutions, colloids and suspensions.
Thus their hesitation around the technology may have been strongly related to the newness of both the content and the use of the SEM to explore that new content.

Melissa turned to formative assessment strategies to address her students’ hesitancy. During her interview, she shared that she instituted an exit ticket that asked, what have you learned, where are you in this unit, how do you feel about the lab report? I did that with chemistry more focused on the content and reflection; over three days they did an exit ticket where they focused on personal discoveries with the SEM, what was most interesting and surprising, and then also some content.” The teacher reviewed and organized the exit slip responses to inform discussion questions she wrote on the white board for discussion at the beginning of the subsequent class so that students would have the opportunity to describe their perceptions, reveal and address misconceptions, offer ideas for how to think about the topic, debate claims and generally become more familiar and comfortable with talking about how to establish the percent composition of mixtures.

Each student was assessed individually. For example, Melissa required individual inquiry laboratory write-ups with student rubrics used to support students in assessing the quality and completeness of their own work. An example of an assignment Melissa used to assess student understanding of key concepts is that she had every student work with a software program to create a digital cladogram (a chart that shows an organism’s evolutionary history) that display morphological data collected on hair cuticle patterns (photo micrographs and drawing) and write an accompanying research report to characterize the details of the hair including cuticle patterns and make and defend claims about classification of each of the hairs.
In addition to using formative assessments and tactics used to intentionally group students, Melissa shared during her interview and in her call-outs that she used several differentiation strategies to address multiple cognitive levels and learning styles to optimize student learning. The topic of differentiation strategies is the third sub category related to pedagogical strategies.

**Differentiation strategies.** A prevalent pattern found throughout the data is that Melissa tended to frequently frame PCK discussions around the affordances of specific teaching strategies and technology used to differentiate instruction and negotiate potential barriers to teaching and learning. Melissa said during her interview:

I think that I did a pretty good job at incorporating different learning styles into the instruction, other students really needed to hear me repeat the instructions and see it on the board, so I coupled verbal explanations with written instructions on the white board and then chunking I guess, breaking down learning goals and pieces of the lab into smaller bites that are more accessible helps students to feel that they can achieve those goals. So the perception of the project doesn’t seem as insurmountable.

The following table A.11 lists barriers Melissa identified on the left and pedagogical solutions she used or developed to test later are on the right column of the following table:
Table A.11

Melissa's Pedagogical Solutions to Barriers & Limitations

<table>
<thead>
<tr>
<th>Barriers and Limitations</th>
<th>PCK related to solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>I felt like I wanted to give my freshman students the freedom and flexibility to encourage that academic autonomy. However, this may have contributed to some students failing to connect the smaller concepts to the big ideas.</td>
<td>I think that more guidance in terms of that integration would have been helpful</td>
</tr>
<tr>
<td>The time constraint was one of the biggest, time with the machine, was one of our biggest constraints.</td>
<td>Each team wanted 30-minutes to an hour on the SEM and in the future I want to be a little stricter about stub preparation and number of stubs that you prepare because even with small classes I was more lenient, but like the feather group had four of five stubs that they had with these beautiful samples of feathers…but like, just learning the process</td>
</tr>
<tr>
<td>[students] were very interested in the integration of art and science and that more time would have been beneficial for me to plan and that would have eased up some of the worry about the size of the project or any kind of fear or anxiety.</td>
<td>I also need to be bit more strict on the time limits for the SEM and to institute a sign-up sheet for each station, so we all know what the rotation is and we don’t lose time trying to remember where everyone has been and still needs to go. That way I’m not as stressed trying to track the rotations and kids can anticipate their next station, which is especially good if they finish the task early on a station and have time to prep for the next one.</td>
</tr>
<tr>
<td>[Teacher feels stretched between supporting students at the SEM and other stations]</td>
<td>Ok, so this kinda ties with better ways that I would teach the content through looking at different strategies, so the first one really would be whole class stub preparation, I tried to have that as a station and I just felt like I was having to run back and forth too much to re-teach; I don’t mind the re-teaching part of course, but for ease of understanding I want everybody to take a half-an-hour and do the sample prep together</td>
</tr>
</tbody>
</table>
and be really clear and really direct.. so I feel that whole class broad instruction would have been good for certain things, like sample prep and maybe modeling more explicitly what to do at each station.

Group roles at stations, I did that at the SEM station, but not any of the other stations and that again makes students feel that the instruction is more individualized and help students to feel a greater level of accountability for what they are learning about.

**Scaffolding**

I think for biology more front loading in terms of nanotechnology of the content, more scaffolding would have been good. I did have one reading which they really loved called Prom 2045 and that was a great hook to engage them at the beginning of the unit, so maybe something at the end that’s some kind of closing article or closing piece that gets them back into the literature and really sums up the unit.

**Left out bio-ethics piece of the unit**

One article that we could have looked at are bio-ethical concerns with nanotechnology, they have been very interested in that topic and I could have had them do some research and reading on that… it’s just time constraints. With the biology, it’s a year of bio squished into a semester and then in the spring is anatomy, so I felt very much like I needed to be careful about what are the central building blocks to prepare for the next units and focus our time on those key topics as much as possible.

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**Technical strategies and solutions.** Melissa reports several strategies she incorporated to address technical barriers and limitations, the fourth category developed from the data. As is the case with all of the teachers in the study, Melissa and her classes negotiated technical limitations throughout her unit of instruction. She said during her interview that in chemistry, students found that not all of the products they chose to examine list the ingredients or percentages on the packaging. Students did on-line searches to find out if companies post the complete list on-line or if there are industry
standards for products such as Earl Grey tea. They found that in some cases, some of the ingredients and or-percentage of ingredients were missing and that there was no industry standard for certain products. Thus it took longer to figure out what the ingredients were that they were seeing with the SEM than see had planned for.

Once they identified the primary component parts of their products, students searched on-line for SEM images of each substance to compare with their own SEM images of their samples to see if the industry product descriptions of the substances in the mixture match what they are seeing in their own image. Though in some cases they could not necessarily positively identify all of the substances found in their mixture, they were able to describe and measure the morphological characteristics of the materials and to categorize samples as heterogeneous or homogeneous products. The teacher said that she realizes the value of this approach and plans to intentionally include this comparative approach to looking at known quantities next year as a key part of the unit plan.

Melissa also contributed to the on-going conversation within the program about building a catalogue of materials that image well and poorly with the SEM when she wrote a call-out that said “on our hair images, frequent charging occurred. Drawing of each strand would be a nice addition for this project.” Although hair consistently imaged fairly well during the summer workshop, three teachers mentioned that students had difficulty with hair charging and with seeing the scales on the strand well enough to characterize the features. Melissa’s comment addresses the scientific goal of identifying variation in terms of how quickly hair may charge and a pedagogical goal of asking students to approach learning how to carefully make and communicate observations of
hair by both drawing and capturing digital images of samples. This is an important contribution because teachers are concerned about maximizing student success by selecting materials that image well, facilitating students’ understanding of why particular materials charge quickly or not and providing multiple approaches to characterizing samples. Thus, Melissa’s observations add to a growing annotated databank that includes images, a catalogue of how materials image and pedagogical strategies for working with the SEM under development by the participants in the program.

A third call-out related to technical strategies and solutions relates to sample preparation, one of the most critical steps in working with the SEM because an improperly mounted sample may either fly up into the machine and stick to the SEM detector thus either breaking the instrument or limiting its capability. If a sample is not correctly oriented on the stub, it becomes difficult or impossible to view particular features of interest and if fingerprints or debris are pressed into the carbon mounting tape along with the sample, the sample will be contaminated. Melissa wrote “carbon tape worked well with pressing samples into surface of table. Should cut hair samples to have an “edge” to see internal structure and have a cross-section.” This reflection is a result of a mini-inquiry performed by the teacher related to how to prepare and mount samples on the stub. In contrast to several of the teacher participants who described the time spent on sample preparation to be wasted time, Melissa shared during her interview that she is deeply considering how to improve upon teaching what she knows to be one of the most critical steps of microscopy.
In addition to technical solutions related to microscopy, Melissa’s next call-out demonstrates that she is anticipating solutions for the diatom unit. She writes, “there are excellent dichotomous keys and links to species identification databases for diatoms. This task is challenging and engaging.” Here the teacher is considering a technique for increasing the degree of higher order thinking in the unit by drawing on a technical reference guide. In anticipation that students may not be proficient at using identification keys, she also recognized an authentic opportunity to involve an adult expert with the necessary expertise to assist students in learning how to key out diatoms. “I made a contact with a diatom researcher for identification help – it would be so neat for students to have a connection with the scientific community in an authentic way.” Informally she spoke about how integrating technical references and expert support into the unit will potentially increase students’ awareness of how scientists negotiate the task of identifying particular features on a diatom useful for categorizing species by drawing on tools available in both analogue and digital forms.

The follow table A.12 provides representative statements categorized as affordances of technology, pedagogical approaches and potential barriers or limitations. Melissa quotations about her own PCK inform the research question “how do teacher participants in the 2012 Project Nanoscience and Nanotechnology Outreach (NANO) program negotiate the inclusion of novel science and novel technology into the science curriculum?"
### Table A.12

Melissa's PCK Related to the Use of Technology in the Unit

<table>
<thead>
<tr>
<th>Affordances of technology</th>
<th>Pedagogical approaches</th>
<th>Potential Barriers or Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Have multiple ways for students to interact with technology-manual, online instructions, and verbal instructions.</td>
<td>how I differentiate, how I make sure that all of the learning styles and needs are met? One way to do that is to have more control over the groups. I picked their groups so that I could identify who I thought would be a team leader in each group and then have students who were really strong in science, students that maybe were a little timid or unsure of their skills so that enabled me, right from the start to have more control or just say, this is your team.</td>
<td>differentiating for students’ abilities levels</td>
</tr>
<tr>
<td>Group roles at stations makes students feel that the instruction is more individualized and helps students to feel a greater level of accountability for what they are learning about.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I think that it’s nice to have all students help with stub preparation and the hands-on, they can’t wait to have that kinesthetic experience</td>
<td>I mean I’m pleased that they had those feelings that’s an integral part of the learning process so and I think that this experience mirrors that of any scientific research and what that feels like in a lab or university setting, I think that the students embraced the project</td>
<td>[There is] more creative and critical thinking involved and understandably more struggle and frustration in getting into that place</td>
</tr>
<tr>
<td>Explore authentic questions as a group using the SEM:</td>
<td></td>
<td>[authentic scientific inquiry experience]</td>
</tr>
<tr>
<td>Are differences in scale/cuticle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Topic</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>-------</td>
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<td></td>
</tr>
<tr>
<td><strong>features quantifiable at the nanoscale?</strong></td>
<td>Will the differences be negligible or significant among mammal species for analysis?</td>
<td></td>
</tr>
<tr>
<td><strong>Scale patterns on hair</strong></td>
<td>All hair samples may look “alike” with the naked eye, how does scale change understanding of morphological similarity?</td>
<td></td>
</tr>
<tr>
<td></td>
<td>All hairs of the same type have a similar morphology</td>
<td></td>
</tr>
<tr>
<td><strong>Cuticle patterns</strong></td>
<td>Discuss how complex it is to group/compare different species based on form and function (morphology).</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Animal hair causes allergies, when in actuality; it is animal dander or saliva that results in allergy symptoms.</td>
<td></td>
</tr>
<tr>
<td><strong>Analyzing percent composition of a mixture and identifying mixture components at the nanoscale using the SEM Phenom.</strong></td>
<td>Model how to create a cladogram and infer evolutionary relationships.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Discuss how complex it is to group/compare different species based on form and function (morphology).</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Animal hair causes allergies, when in actuality; it is animal dander or saliva that results in allergy symptoms.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>When examining the mixture of a food item, the percent composition will be identical to the listed masses for each serving size</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mixtures that students may have encountered (air, water, honey, yogurt) may look pure, but are really mixtures of multiple substances.</td>
<td></td>
</tr>
<tr>
<td><strong>Cuticle patterns distinguish animal species, with coronal scales more commonly found in the hairs of small rodents and bats, spinous (petal-like scales) found in mink, seals, and cats, while imbricate (flattened) scales are found in humans and many other animals. Looking at differences in scale and cuticle patterns using SEM.</strong></td>
<td>Discuss myriad definitions of evolution.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shorter haired animals cause fewer problems in terms of allergies.</td>
<td></td>
</tr>
</tbody>
</table>
Discuss and understand the distinction between homogeneous and heterogeneous mixtures, as well as differences in physical/chemical properties depending on scale. Ingredients can be identified based on shape/size at the nanoscale.

We need another Phenom!

More time would have been beneficial for me to plan, to respond and shift in response to what I’m seeing in the classroom. That would have eased up some of the worry about the size of the project or any kind of fear or anxiety. So I think that three weeks [in the future] would be just right for this unit, I mean I could easily do four weeks, but three weeks would be very reasonable.

Time constraint was one of the biggest, time with the machine, was one of our biggest constraints.

Changes in Teacher’s Thinking

The fifth category developed from Melissa’s data is changes in teacher’s thinking. This category is comprise of three sub-categories related to changes in Melissa’s thinking about how to improve upon the unit; the first two sub-categories relate to PCK changes in the structure of the unit and technical PCK changes. These categories inform the first sub question, *how, if at all, do teachers’ metastrategic thinking and PCK change between the summer workshop and the reflection period following the implementation of the Project NANO unit?* The third sub category relate to teacher learning and informs the sub question *do teachers demonstrate scientific content knowledge gains in response to the 2012 Project NANO summer workshop?*
**Changes in PCK.** Changes in Melissa’s pedagogical content knowledge (PCK) inform new ways she is considering scaffolding of the unit to focus student thinking to provide for deeper analysis of topics. She wrote in her call-outs and said in her interview that in terms of scaffolding each unit, she will replicate in all of her classes the “front-loading” she did in chemistry this year with similar pre-teaching activities such as watching videos on nanoscale science and technology and discussing technical applications of nanotechnology and exploring foundational concepts related to the key learning objectives for the unit. She will increase the number of formative assessment strategies involving group discussion to ensure that students are not incorporating misconceptions into new knowledge and to help students connect concepts with the big ideas more regularly throughout the unit. She also plans to rewrite the instructions for each of the stations based on her new knowledge of how students perceive specific language and then model each activity more explicitly next year. In addition, she plans to assign more explicit roles within each group with well described deliverables for each role.

**Changes in Technical PCK.** Changes in Melissa’s Technical PCK that she identified in her call-outs and during the interview discussion and classroom observations involve providing more discrete guidance for working with sample collection and preparation including gathering samples on a fieldtrip, prepare samples prior to the arrival of the SEM and have the students work as one group to prepare stubs and slides. Melissa also spoke of learning the importance of restricting the number of samples to be loaded for examination of with the SEM as a key time budgeting issue.
She spoke about the improvements in her ability to clearly and succinctly guide students through the sample preparation and load protocols for the SEM and through the controls of both of the microscopes in a facilitative rather than strictly directive manner. Melissa acknowledged during her interview that there does seem to be a relationship between her stress over time and how directive she tends to be with students, which she says is all the more reason to learn to be strict with the number of samples each group prepares to examine and the number of people in a group, each of whom must have time on the controls which the others are to remain engaged in thinking about the image on the SEM or Leica screen.

During her interview, Melissa shared her thought that when too many students are around the SEM or Leica, some tend to get bored and become distracting to others and thus waste more of everybody’s time. With better defined roles and less people in a group charged with completing explicitly defined tasks, students will be more likely stay engaged at the instruments. She also noticed that at the stations that do not involve microscopy, students finished the stations before the end of the allotted time period and quickly became distracted. She thought that better defining the overall project may lead to students becoming less dependent on the teacher calling out the station rotations and simply moving on to complete other tasks related to generating the science report while waiting for the rotations to occur.

**Teacher’s scientific content knowledge gains.** And finally, data that informs the third sub-category related to changes in thinking is teachers’ scientific content knowledge gains. During the writing of the CoRe, Melissa developed a set of testable questions she
and her students successfully pursued. Examples of these questions are: “Are differences in scale/cuticle features quantifiable at the nanoscale? Will the differences be negligible or significant among mammal species for analysis? And will potential charging on sample prevent differences in cuticle/scale patterns from being visualized?” Each one of these questions led to working with students to incorporate these questions in their inquiry such that everyone involved learning more about the technical affordances and limitations of the microscopes to explore ideas.

**Summary of Melissa’s Case**

Melissa’s case is significant for two reasons. This is a case description of a teacher who drew upon an initial experience integrating nanoscale science and technology into the curriculum to consider how to scaffold and organize learning for each class as students move from freshman biology to sophomore chemistry to junior biochemistry. She also provided an example of how foundational ideas about nanoscale science and technology provide an important basis for teachers to plan a more open-ended inquiry experience that is integrated with the curriculum rather than an add-on that does not fit logically within the sequence of the larger lesson cycle. Melissa’s prior experience with nanoscale science and technology as a recent graduate student and her work to complete the pre-requisite assignments significantly contributed to her level of preparedness to design her unit during the summer workshop which in turn provided the opportunity for her coach to respond to her explicitly communicated thinking and support the refinement of her approach to integrating instructional elements such that students experienced a successful introduction to nanoscale science. Additionally, she shared that
the Vygotskian framework and use of familiar unit planning strategies such as the Backwards Planning approach she recently learned in her graduate education courses also contributed to her success at planning within the framework and being able to clearly communicate her thinking using these structures.
APPENDIX E

CoRe TEMPLATE
## Content Representations (CoRe)

### This CoRe is designed for: (course name & grade level)

<table>
<thead>
<tr>
<th>Big Ideas:</th>
<th>A:</th>
<th>B:</th>
<th>C:</th>
</tr>
</thead>
<tbody>
<tr>
<td>What you intend the students to learn about this idea.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Why is it important for the students to know this?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>What else do you know about this idea (that you do not intend the students to know yet?)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Difficulties/limitations connected with teaching this idea:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Common misconceptions students hold about this idea:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Difficulty/limitations connected with use of scientific instruments:</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
What are some learning opportunities that are made possible with the use of the SEM technology:

<table>
<thead>
<tr>
<th>Knowledge about students' thinking which influences your teaching of this idea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knowledge about students' thinking that influences how you integrate technology into the lesson</td>
</tr>
<tr>
<td>Other factors that influence your teaching of this idea.</td>
</tr>
<tr>
<td>Teaching procedures (and particular reasons for using these to engage with this idea).</td>
</tr>
<tr>
<td>Specific ways of ascertaining student's understanding or confusion around this idea (include likely range of responses.)</td>
</tr>
</tbody>
</table>

CoRe template modified from a template created by Loughran, Berry and Mulhall (2006).

*Note: Cell sizes reduced to fit the page for the purposes of the appendix*
APPENDIX F

PRE AND POST SURVEY
Section I – Demographic Survey

1. Are you an in-service or pre-service teacher?
   - In-service
   - Pre-service

2. What science courses do you teach? (check all that apply)
   - Biology
   - Physics
   - Chemistry
   - AP _____________
   - IB _____________
   - General Science
   - Integrated Science
   - Middle School Science
   - None of the above

3. How many years of experience do you have teaching the main discipline you currently teach?
   - 0
   - 1-3 years
   - 4-5 years
   - 6-10 years
   - 11-15 years
   - > 15 years

4. Estimate how many college level science courses that you took that involve a laboratory experience.
   - 1 to 3
   - 4-6
   - 7-10
   - > 10

5. Do you currently use scientific instruments with a digital interface in the courses you teach?
   - Yes
   - No
   - Not applicable
6. Do you teach science as inquiry?
   o Yes
   o No
   o Not applicable
7. Do you have any experience working with a scanning electron microscope in any capacity?
   o Yes
   o No
8. If you answered yes to the last question, please check all that apply:
   o I have used an SEM in the science classes I teach
   o I have used an SEM in science classes I took as a student
   o I have used an SEM in a professional research capacity
   o I have used an SEM in a conference workshop
   o I have used an SEM that was available as part of a demonstration at a conference

Section II - Written exam (same for both pre and post survey)

Multiple choice

3. Circle the unit of measurement used to measure the head of a pin.
   a. meters
   b. millimeters
   c. micrometers
   d. nanometer
   e. femotometer

4. Which of the following cannot be loaded into an SEM? (circle all that apply)
   a. Magnetic metal
   b. Wet material
   c. Live organisms
   d. Organic material
   e. None of the above
Open-ended short answers

5. What is the difference between an optical microscope and a scanning electron microscope (SEM)?
6. Describe five key components of the scanning electron microscope.

7. Describe safety protocols related to working with secondary level students and a table top SEM.

8. Provide a brief description of how you might integrate optical and electron microscope in a course to instruct students on form and function related to the discipline you teach (use the back of the page if you need more room).
APPENDIX G

PRE AND POST SURVEY RUBRIC
Project Nanoscience and Nanotechnology Outreach
June 21, 2011
Pre and Posttest scoring guide

Section I – Written exam (bolded choice is the correct choice or choices)

Multiple choice

1. Circle the unit of measurement used to measure the head of a pin.
   
   f. meters
   
   g. **millimeters**
   
   h. micrometers
   
   i. nanometer
   
   j. femotometer

2. Which of the following cannot be loaded into an SEM? (Circle all that apply)
   
   a. **Magnetic metal**
   
   b. **Wet material**
   
   c. **Live organisms**
   
   d. Organic material
   
   e. None of the above
### Short answer section

<table>
<thead>
<tr>
<th>Points – 1 being lowest score; 3 being highest score</th>
<th>1. Weak/ No Evidence</th>
<th>2. Emerging</th>
<th>3. Proficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>What is the difference between an optical microscope and a scanning electron microscope (SEM)?</strong></td>
<td>Response states that the participant either doesn’t know or provides incorrect information</td>
<td>An optical microscope uses light for magnification up to 1000 x and use a simple lens. An electron microscope uses electrons for magnification up to a million x and produce a greyscale image.</td>
<td>An optical microscope uses light for magnification up to 1000 x. An electron microscope uses electrons for magnification up to a million x. The electron wavelengths are much shorter than proton wavelengths and therefore provide higher level of magnification, produce a greyscale image and project a more detailed field using an electrostatic or electromagnetic lens.</td>
</tr>
<tr>
<td><strong>Describe five components of the scanning electron microscope</strong></td>
<td>Respondent only lists components that are found on an optical scope such as the lens, objectives, transilluminator, etc.</td>
<td>Respondent names at least three of the following features: source, thermionic guns, magnetic lens, electromagnetic lens, sample cup, sample chamber, detectors, vacuum, vacuum chamber.</td>
<td>Respondent names at least five of the following features: source, thermionic guns, magnetic lens, electromagnetic lens, sample cup, sample chamber, detectors, vacuum, vacuum chamber.</td>
</tr>
<tr>
<td><strong>Describe safety protocols related to working with secondary level students and a table top SEM.</strong></td>
<td>Response states that the participant either doesn’t know or provides incorrect information</td>
<td>“Standard lab protocols”, including gloves, eye protection.</td>
<td>Before loading the SEM make sure the sample is dry, dead, non-magnetic, stuck down and spun down four clicks. No loading without a supervisor. No loading samples without an OK from a trained adult. Optional: A log must be kept to notate name of users, date,</td>
</tr>
</tbody>
</table>
| Provide a brief description of how you might integrate optical and electron microscope in a course to instruct students on form and function related to the discipline you teach. | Response states that the participant either doesn’t know or provides incorrect information | Response briefly describes at least one “big idea” in science related to exploring matter with an SEM | Response names 3-8 big ideas in science related to the form and function of matter
Names a specific place in the curriculum that the two types of microscopes would enhance
Names 2-3 or more learning outcomes related to Oregon science content standards |
APPENDIX H

INTRODUCTION TO RESOURCE FOLIOS SUMMER WORK SHOP HANDOUT
Resource Folios

A complementary representation of concrete examples that are illustrative of PCK for a topic.

The groups of teachers involved in Project NANO represent educators on the leading edge of science teaching so it’s important to capture their ideas for how they draw upon PCK to negotiate the inclusion of novel science and technology into the curriculum.

a. Our team is interested in understanding how the program supports teacher and student learning

b. I am interested in adding to our understanding of teacher thinking

Resource Folios consist of two parts;

- Content Representations (CoRe) and
- Professional and Pedagogical Experience Repertoires (PaP-eRs)

The CoRe is a tool used by teachers to prepare for planning a two-three week unit of instruction that incorporates nanoscale science and technology and will be framed around unifying concepts and big ideas:

Unifying concepts and processes

“Unifying concepts—such as energy, patterns, systems, models, change over time, form and function, and others—connect different areas of science in deep and meaningful ways.” NSTA website
Big ideas

Big ideas are crosscutting concepts that provide students with powerful ideas to help them understand the natural world. The nine big ideas in nanoscale science established by an NSF sponsored committee are:

1. “Size and scale
2. Structure of matter
3. Forces and interactions
4. Quantum effects
5. Size-dependent properties
6. Self-assembly
7. Tools and instrumentation
8. Models and simulations
9. Science, technology and society”

(Stevens, Sutherland & Krajcik, 2009, p.3)

Content Representations (CoRe) is way to:

a. Reflect on fundamental ideas related to teaching a particular topic
b. Develop and communicate an overview of a particular approach to teaching a topic using specific strategies
c. Provide insight as to the rationale for the choice of strategies in response to what is known about the topic and particular groups of students
d. Document thinking in such a way that can be shared for collaboration and for building the body of science education knowledge.
i. Typically this would be more important for novice teachers or those teaching out of discipline; however in this case, nearly every teacher on the planet is a novice when it comes to using virtual field experiences as a vehicle for engaging students in doing inquiry.

**Professional and Pedagogical Experience Repertoire – PaP-eRs**

A narrative reflective account from teachers that provides highlights of insight on a teacher’s approach to a particular piece or aspect of science to be taught. For Project NANO, PaP-eRs include:

1. Call-out reflections – dialogue boxes added to the CoRe throughout the lesson cycle

2. The unit of instruction designed in the class

3. Focus group
APPENDIX I

FOCUS GROUP QUESTIONS
Focus Group Questions

As a way for teachers to focus their thinking, I asked the teachers to review their CoRe and call-out reflections prior to joining the one-hour focus group or one-on-one interview scheduled after the teachers had implemented their Project NANO unit. Upon arrival to the interview, teachers were given a hard-copy KWL chart as a tool used to collect their thoughts before responding to each of the following questions (see below).

Recall that the participants who implemented their unit of instruction by the end of February were given a choice to participate in the focus group or invite me to their classroom for a one-on-one interview. The following questions used for both the focus group and the individual interviews are designed to loosely guide the discussions rather than drive the open-ended interviews.

Project NANO Focus group Questions

I. Pedagogical Strategies related questions

1. Briefly describe the instructional unit that you taught as part of your involvement in Project NANO.

2. Start out by looking at the “What I know” section of the KWL chart and list out your ideas regarding how you approached teaching the content you covered in this unit. Then share your ideas with the group.

3. Briefly describe your ideas of how you designed the lessons to appeal to the various learning modalities in your class?
4. Now, fill out the KWL chart column “what I learned” with your ideas for how effective you consider those differentiation strategies to have been.

5. Look at the “what I want to know” section of the chart. Please list ideas related to classroom management strategies you used to increase the level of student engagement for students working with technology to investigate their inquiry in the Project NANO unit.

II. Project NANO program related questions

6. Did your Project NANO workshop instructors and coach (Mike Blok and Keith Grosse) affect the way you taught the unit?

7. Do you feel that the support from Project NANO is influencing your ability to teach science as inquiry?

8. How confident did you feel about working with the students to teach novel content working with novel science technology after teaching the Project NANO unit you designed over the summer?

9. Do you think that you will continue to include nanoscale science and nanotechnology in your science teaching practice in the future?
APPENDIX J

KWL CHART
<table>
<thead>
<tr>
<th>What I Know</th>
<th>What I Learned</th>
<th>What I Want to Learn</th>
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APPENDIX K

UNIT PLANNING TEMPLATE
Unit Planning Template

(Becker, 2008)

This template was provided in a digital format on the course website. Each of the cells expands with writing and teachers were explicitly asked not allow the size of the cell to guide the length of response.

Unit Title:       Teacher Name:

**Knowledge**: Please use the provided space to describe the knowledge outcomes you anticipate addressing in your unit.

Example of a knowledge outcome could be ‘When liquid water disappears, it turns into a gas in the air’, or ‘In all organisms, the instructions for specifying the characteristics of an organism are carried in DNA’ for high school biology.

<table>
<thead>
<tr>
<th>Knowledge Outcomes:</th>
<th>Linked Standard (if appropriate)</th>
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**Skills**: Please use the provided space to describe the skill outcomes you anticipate addressing in your unit.

Examples of skills could include process skills commonly used in science (e.g. measurement, explanation, controlling variables) or a habit of mind (e.g. critical reasoning, skepticism, identifying bias).

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<thead>
<tr>
<th>Skill Outcomes:</th>
<th>Linked Standard (if appropriate)</th>
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</table>
**Experiences:** Please use the provided space to describe the experience outcomes you anticipate addressing in your unit.

Examples of experience outcomes could include a specific classroom activity, an engineer speaking to the class, or a visit to a scientist’s laboratory.

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<thead>
<tr>
<th>Experience Outcomes:</th>
<th>Linked Standard (if appropriate)</th>
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**Assessments:** Please use the provided space to outline and describe (in as much detail as possible) the assessments you anticipate using during your unit.

Examples of assessments could include in-class assessments, questioning strategies, homework, end of unit assessments, etc.

<table>
<thead>
<tr>
<th>Assessments:</th>
<th>Linked Outcomes (K, S, E)</th>
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<tbody>
<tr>
<td>Please feel free to attach drafts of these assessments if they are available.</td>
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**Pedagogical Strategies:** Please use the provided space to outline and briefly describe the pedagogical strategies you anticipate using during your unit.

Examples of pedagogical strategies could include group work, individual investigations, direct instruction/lecture, class discussions, etc.

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<thead>
<tr>
<th>Pedagogical Strategies:</th>
<th>Linked Outcome (K, S, E)</th>
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Calendar of Unit – Weeks 1 & 2:

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<th>Monday</th>
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Note: Cell sizes reduced to better fit the appendices
Appendix L
UNIT PLAN KNOWLEDGE, SKILLS, EXPERIENCES SCORING GUIDE
Unit Plan Knowledge, Skills, Experiences Scoring Guide (Becker, 2008)

Evaluation Criteria for a Student-Centered Science Inquiry/Engineering Design Project/Unit

Consider the Science Inquiry/Engineering Design activity/unit before you. Evaluate each of the five curriculum elements using the following criteria that are based on “best practices” from current research literature on effective student teaching and learning in science.

Score a criterion statement with a “3” if the science activity/unit is exceptional and represents the best practice for learning science through inquiry.

Score a criterion statement with a “2” if the science activity/unit contains, at a functional level, the best practice for learning science through inquiry.

Score a criterion statement with a “1” if the science activity/unit provides an opportunity for the best practice to occur but it is not explicitly included in the activity/unit and could be added with appropriate modifications.

Score the criterion statement with a “0” if there is not an opportunity to include the best practice in the activity/unit.

The curriculum element totals will enable you to evaluate the relative strengths and weaknesses of various student-centered science inquiry and engineering design activities. It is unlikely that a single activity/unit can score 2’s and 3’s in all of the evaluation criteria. However, your goal should be to try and balance the strengths and weaknesses of the science inquiry/engineering design activities/units to maximize the number of best practices included in each of the five curriculum elements.


Taking Science to School: Learning and Teaching Science in Grades K-8, Committee on Science Learning, Kindergarten Through Eighth Grade, Richard A. Duschl, Heidi A. Schweingruber, and Andrew

## Evaluation Criteria for Science Inquiry/Engineering Design Curriculum Unit

### Knowledge and Concepts

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- **e.** Appropriate grade level **conceptual knowledge** instruction is organized around a big idea in science.
- **f.** Clear expectations are stated, in student language, about the **science knowledge objectives** for students.
- **g.** Oregon science grade-level **benchmarks/standards** are explicitly embedded in the unit.
- **h.** New **conceptual knowledge** is introduced with developmental links to prior learning.

### Science Inquiry and Engineering Design Skills

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<td>c.</td>
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- **a.** Students generate testable and appropriate **SI/ED** that uses the targeted science content.
- **b.** Students **identify variables** and develop **inquiry design(s)** and **data collection** protocol(s).
- **c.** Students present and critically evaluate their **empirical data and results** (precision and accuracy) using appropriate methods.
- **d.** Students make and defend **knowledge claims** from a critical analysis of their SI/ED results and prior knowledge.
- **e.** Students employ **appropriate technology** when conducting their investigation and presenting their findings.

### Student Experiences

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- **a.** Students experience new **science concepts** in the context of real world applications and/or issues.
- **b.** **Accommodates student diversity** in strategies, approaches, abilities, cultural perspectives and learning styles.
- **c.** Unit facilitates student use of **meta-cognitive strategies** to identify, monitor, and regulate learning.
- **d.** Students are prompted to pursue **extensions and additional and/or deeper investigations**.

### Learning Community

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- **a.** Students engage in activities or discussions that draw out **what they know or how they know**.
- **b.** Students work in small **collaborative peer groups** to plan and execute the science inquiry.
- **c.** Students are encouraged to develop and share **inquiry ideas and resources** with the full class.
- **d.** Students **communicate and defend the results** of their inquiry to their instructor and peers.
### Assessment of Student Achievement

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</tr>
<tr>
<td>a.</td>
<td>Assessments probe for students’ <strong>prior understanding</strong> of targeted concepts and skills.</td>
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<tr>
<td>b.</td>
<td>Assessments probe for student misconceptions with opportunities to <strong>self-assess</strong> their learning.</td>
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<tr>
<td>c.</td>
<td>Assessments provide multiple chances and formative options to <strong>revise thinking</strong></td>
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<tr>
<td>d.</td>
<td>Assessments provide an inventory and/or <strong>Post-assessment</strong> of knowledge.</td>
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<td>e.</td>
<td>Student work samples demonstrate the achievement of <strong>knowledge</strong> and <strong>skills</strong> learning objectives through <strong>SI/ED experiences</strong></td>
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/15  Curriculum element total
APPENDIX M

FIELDNOTES FORMAT
Fieldnotes Format

Fieldnotes were taken throughout each of the three teacher professional development summer workshops and throughout each of the secondary level classroom observations. Prior to the first summer workshop, I planned out the following format for the notebooks:

1. Each workshop has a dedicated notebook or set of notebooks
2. Each notebook is bound and no pages will be removed
3. The first five pages of each notebook are to be left blank to leave room for post-workshop reflections and post observation reflections
4. Each page of the notebook indicates the number of the workshop (1, 2 or 3), the day of the workshop (1-5) and the date
5. On the first day of each workshop, the notes entail a drawing of the classroom and laboratory set up, the class seating arrangement and notes about what is written on the white boards and posted on the bulletin boards for the participants
6. Notes include numbered references to any handouts
7. Notes are handwritten
8. The researcher will circulate throughout the class taking notes as a participant observer during the workshops and as a non-participant observer during secondary classroom observations
9. When teams, group or individuals are at a microscope, I will begin by asking permission to take notes and ask questions and I will walk away from those who asked to have “free play time” to simply look at samples without interruption
10. Notes are focused on evidence of how teachers are drawing on content knowledge and other forms of pedagogical content knowledge to learn new content and technology and to design new units of instruction.
11. At the end of each day, I will review the notes, clarify spelling where necessary and add my own reflections within brackets
12. I established the following set of codes for note taking prior to the beginning of the first workshop:
APPENDIX N

RULES OF TRANSCRIPTION
Rules of Transcription

1. Nearly verbatim transcription (see exception in #2 and #3)

2. Stuttering and habitual verbalizations (such as um, uh, hmmm) are omitted to enhance clarity

3. The word kinda is replaced with “kind of”

4. Names of people are changes to pseudonyms

5. Place names and titles are omitted or given pseudonyms

6. Each speaker on a new paragraph

7. Dash between speaker’s name and text

8. Use complete sentences when possible

9. Use punctuation as correctly and accurately as possible

10. Break up new ideas into new paragraphs

11. Note the reason for particularly long pauses explicitly in the text within brackets

12. If a teacher refers to something she or he shares/gives to the research to exemplify points made during the interview, cite the artifacts as specifically as possible with a footnote

Transcription Key

13. Ellipse (=) for sudden or abrupt speech

14. Long ellipsis (…) for long pauses

15. Short or two dot ellipsis (..) for shorter pauses

16. Empty parentheses ( ) for cannot hear what is being said

17. Smile <SM> for smiling quality

18. Brackets [ ] for transcriptionist insertion