Exploring Student Engagement with a Nanotechnology Module for Middle School Developed Using the Model of Educational Reconstruction

Martyna Laszcz

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EXPLORING STUDENT ENGAGEMENT WITH A NANOTECHNOLOGY MODULE FOR MIDDLE SCHOOL DEVELOPED USING THE MODEL OF EDUCATIONAL RECONSTRUCTION

A Thesis Presented
by
MARTYNA LASZCZ

Submitted to the Office of Graduate Studies, University of Massachusetts Boston, in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE
May 2021
Applied Physics Program
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ABSTRACT

EXPLORING STUDENT ENGAGEMENT WITH A NANOTECHNOLOGY MODULE FOR MIDDLE SCHOOL DEVELOPED USING THE MODEL OF EDUCATIONAL RECONSTRUCTION

May 2021

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Nanoscience and Nanotechnology (NST) is a booming multi-disciplinary field, with significant implications towards scientific and technological innovation. The growing reach of NST has created a demand for a skilled and scientifically literate workforce. However, NST is typically inaccessible outside of specialized contexts. Therefore, there is a need for bringing NST into the K-12 classroom.

In this study, we explored the use of technology-based NST modules to introduce middle and high school students to the field, wherein students unpacked an NST tool, the atomic force microscope (AFM), to learn about basic NST-related science concepts. The module created for this study was developed drawing from constructionist frameworks and
the model of educational reconstruction (MER). MER is a cyclical process that requires educators to consider existing scientific content structures, student knowledge and ideas about a topic, as well as teacher perspectives when designing a meaningful learning experience that attends to student and teacher needs. MER can also have positive impact on teachers’ pedagogical content knowledge (PCK) about a subject, bridging the gap between scientific content and facilitation.

We have designed, revised, and implemented an NST module for grade 8 over the course of two years. Student survey responses, classroom videos, individual and group student work, and teacher interviews were analyzed for recurring themes and significant changes between module implementations. Our results suggested that the process of constructing and reconstructing an NST learning experience made for meaningful modules, with students demonstrating increased understanding of the AFM and increased interest in science, technology, engineering, mathematics (STEM) as a whole after engagement with the module content. Interviews with the collaborating teacher suggest that being involved in the module development process may have impacted her PCK about NST. Based on our results, we can use of a technological tool to introduce students to a novel discipline. We also suggest the use of MER for NST module development.
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CHAPTER 1

INTRODUCTION

1.1 Introduction

My study involved developing application-based nanotechnology modules for middle and high school students. The modules were developed with the intent to introduce grade 8 and 9 students to the growing field of nanoscience and nanotechnology (NST). In particular, this study took an application-based, technology-rich approach, bringing an industry tool (the atomic force microscope, or AFM) to classrooms. The NST modules that incorporate a constructionist (Papert, 1980) approach, were developed using the Model of Educational Reconstruction (MER) (Duit, Gropengiesser, Kattmann, Komorek, and Parchmann, 2012). In learning experiences shaped by constructionist frameworks, based on constructivist frameworks, the belief is that knowledge is built upon, not acquired. Students learn by making, doing, collaborating and sharing their work (Papert and Harel, 1991). To capture the essence of the constructionist approach, we employed the MER framework. The MER is a framework for developing a learning experience and cyclically revising it to better attend to student ideas and the teacher’s perspective. The MER has been, for many topics in science, a powerful tool in gaining insights about student’s ideas, beliefs and misconceptions about scientific concepts (Saarelainen and Hirvonen 2009; Felzmann, 2017; Niebert and Gropengiesser 2013). This study aimed to study the evolution of student ideas and understanding about NST
concepts as a result of engagement with the module, and the effectiveness of teacher participation in the revision process towards preparing teachers to implement NST in their classrooms. My study was exploratory in nature, where I intended to gain insights towards planning and teaching NST at the late middle to early high school level.

1.2 Rationale

Nanotechnology, a relatively new yet quickly booming industry, has impacted nearly every field of science and has consequential societal implications (Roco and Bainbridge, 2005). The growing reach of nanotechnology has led to calls for NST education initiatives and research (Friedersdorf, 2020). Despite this, NST remains largely inaccessible to the K-12 classroom. The tools, resources, and know-how are often limited to specialized research contexts, such as research universities. A significant part of NST education research has focused on undergraduate students, who are more likely to have access to NST resources at their universities (Furlan, 2009; Chopra and Reddy, 2012; Gottfried, 2011). However, research has suggested that early exposure to NST may positively impact students’ interest in NST-related STEM careers (Friedersdorf, 2020). As nanotechnology is expected to grow, so is the demand for scientifically informed citizens and a technologically skilled workforce. The study presented here responds to the suggestions made to bring NST concepts and ideas to K-12 classrooms, utilizing an application-based approach. With this constructionism-inspired approach, students are introduced to a discipline by first exploring its’ applications through a technological tool. As students reverse engineer a tool, they learn about the underlying concepts that contribute to its’ functions and resulting effects of its use.

The presented study used the MER as a framework for the development of the modules. There has been limited reported work on use of the MER in NST, leaving space
to study the effectiveness of the framework in an NST context (Stavrou, et al., 2015). The MER framework is based on finding alignment between students’ learning needs and teachers’ planning and facilitation practices. The need to fine tune the teaching and learning requirements consequently creates a need to understand gaps in teacher preparation. Use of MER allowed us to collaborate with classroom teachers both as co-developers as well as practitioners for the NST modules. The relevant concepts of NST, being a newly emerging field, were unfamiliar to K-12 teachers. Teachers need support not only in understanding the new concepts, but also in understanding ways to successfully integrate NST concepts in their classrooms. Studies that focus on teachers’ preparation and training around NST call for providing teachers with relevant professional development in introducing NST concepts in their classrooms (Huffman, Ristvey, Tweed Palmer, 2015). In response, this study aims to consider the teacher perspective, through collaboration with classroom teachers towards developing innovative NST modules and further reflect on how the research-practitioner model supports teacher development.

1.3 Research Questions

The study I present responds to the demand for exposure to NST in K-12 classrooms, particularly in middle school where reported work is limited. To do so, we employ the MER, a powerful framework for informing science education, that has not been used extensively in NST, to design, evaluate, and revise a constructionist learning experience. Insights towards student readiness and interest in studying NST are noted during the revision process. This study is part of a larger effort to make nanotechnology more accessible to grades 8 and 9 by creating application-based modules where students are exposed to industry tools and technology to explore new NST concepts. In this thesis, I will attempt to answer the following research questions:
1. How did students engage with technology- and application-based modules for teaching NST to grades 8 and 9?

2. What are the affordances of using this format to teach novel science concepts?

3. How was the MER useful in preparing a teacher to teach an NST module, and developing her pedagogical content knowledge?

### 1.4 Theoretical Frameworks

In this section, the theoretical frameworks we drew from to design, facilitate, evaluate, and revise the module are discussed. The module draws from Constructionist theories of learning to inform the learning objectives and activities chosen during the module. It also draws from Model of Educational Reconstruction (MER), a cyclical process used to create, test, and evaluate a learning experience by taking into account students’ engagement and beliefs about a topic before, during, and after the module. In combining these frameworks, we can design a hands-on, technology-based learning experience that suits student and teacher needs by evaluating and revising the module.

#### 1.4.1 Constructivism, Constructionism, and Technology

Constructivist theories of learning propose that knowledge is not acquired or given but built upon previously held knowledge (Ackermann, 2001). Constructivism holds that learning is an active process where communication and collaboration between peers, in a student-centered environment plays a significant role in facilitating learning (Anderson and Kanuka, 1999). Constructivism calls for creating learning environments where students are given opportunity to build upon previously held beliefs or ideas during the learning experience. Constructionism, inspired by constructivism, still proposes...
that knowledge is built upon itself. However, it calls for the learning experience to be centered around “making” or “doing”’ (Papert and Harel, 1991). In constructionist learning environments, students build something tangible that they can then share with other students, such as a model created during a design task. Working with physical artifacts to engage learners in a particular discipline is the core of constructionism (Papert, 1980). Social interaction, similarly to constructivism, is an essential aspect of constructionism. As students work with their peers, they can verbalize their own thinking and process their thoughts out loud, listen to others’ line of thinking, and learn from each other through immediate feedback (Kafai and Harel, 1991). When students work together, they are able to develop their content knowledge as well as strengthen their collaborative skills. The teachers’ role in constructionist learning environments is being a facilitator of the collaborative process between students while ensuring that they meet the set learning objectives (Harel and Papert, 1991).

Research focused on teaching scientific concepts through learning environments that emphasize the use of a physical artifact, such as a technological tool, and social interaction has demonstrated positive outcomes and implications. Jones et al., (2003) found that high school biology students’ content knowledge had improved and attitude towards the subject were positively impacted after participating in a study of viruses by remotely operating an AFM with haptic feedback, versus those who did not experience haptic feedback during operation, suggesting touch plays an important role in exploring a scientific concept. Alimisis and Kynigos (2009) suggest that physically controlling robots is just as critical to understanding their build and behaviors as building and programming them, upon exploring a constructionist approach to robotics. Korwin and Jones (1990) explored and compared learning experiences about geodesic domes for eighth grade students, having one class engaged in building physical models with pipe cleaners and other materials, while the other included only reading and lecture about geodesic
domes and their geometry. After comparing test scores, Korwin and Jones reported significant increase in students’ knowledge about geodesic domes as a result of engagement in hands-on, technology-based activities as compared with lecture-based learning. Lati and colleagues (2019) found that a series of hands-on labs exploring silica aerogel to discover nanoscience concepts positively promote high school student interest in NST.

This study drew from the constructionist approach as we emphasized student engagement in a hands-on, collaborative, technology-based experience to unpack NST concepts. The module engaged students in exploring the AFM, a piece of technology used in nanoscience, as they engage in reading, discussing, observing demonstrations and modeling tasks working with their classmates. As students worked with a tangible object and collaborate with their peers during these multi-modal experiences, they discovered and built their knowledge of NST concepts through studying the AFM as an NST tool. During the multiple experiences surrounding the AFM, students worked together, shaping their beliefs through immediate feedback from their peers in real time, meeting the social component of a constructionist approach. In turn, we believe providing multiple opportunities allows for active engagement in learning that is crucial to support a constructionism-inspired learning experience.

1.4.2 The Model of Educational Reconstruction

The MER is a framework created to improve the development of science learning experiences by attending to the relevant scientific content, as well as students’ ideas, and teacher perspectives surrounding that content (Duit, et al., 2012). It is a cyclical process that entails clarification of the content, taking into account student and teacher needs, and developing and further revising planned learning experiences. The presented study drew from the MER framework by applying the cyclical revision process to the created
module, and by attending to student ideas and the teacher perspective. The MER is discussed in detail in Chapter 3.
CHAPTER 2

NANOSCIENCE AND NANOTECHNOLOGY IN EDUCATION

2.1 Defining Nanoscience and Nanotechnology

The prefix “nano-” generally means one billionth \((1 \times 10^{-9})\) of a unit, typically relating to size (i.e. “nanometer” implies one billionth of a meter) (Poole Jr and Owens, 2003). Accordingly, the term “nanoscience” refers to the study of objects, their properties, and their behaviors at the nanoscale (Bayda, Adeel, Tuccinardi, Cordani, Rizzolio 2019).

Insights on nanoscale entities and their properties lend themselves to nanotechnology, a highly multidisciplinary field that draws from applied sciences and technology. Nanotechnology, specifically, is the design, characterization, production, and application of structures, devices, and systems, by controlled manipulation of size and shape at the nanometer scale, typically resulting in at least one novel characteristic property (Bawa, Bawa, Maebius, Flynn and Wei, 2005). At these scales, materials may exhibit a range of unusual chemical and physical properties that may differ in important ways from the properties of bulk materials (also known as “size-dependent properties”). For example, gold nanoparticles reflect red light in particular lighting conditions, a behavior that does not occur at a macro-scale (Bayda, et al., 2019). Materials that are comprised of nanostructures exhibit interesting mechanical properties as well. Metals made up of particles with particle size of around ten nanometers are much harder, and therefore
more resilient, than typical metals having a particle size of around a hundred nanometers (Berger, 2016). Novel material properties, such as interesting size dependent phenomena and differing mechanical properties, have had a striking impact on technology. Nanotechnology has improved existing industrial processes, materials, and applications by scaling them down in order to ultimately fully exploit the unique quantum and surface phenomena that matter exhibits at the nanoscale. The study of these properties has led to advances in nearly every scientific field (Roco and Bainbridge, 2005).

2.2 Significance of NST

Following the Nobel prize winning invention of the Scanning Tunneling Microscope (STM) in 1981, and its ability to image and manipulate individual atoms, nanotechnology has vastly expanded as a field (Bayda, et al., 2019; Rugar and Hansma 1990). In response to the field’s growing importance, the National Nanotechnology Initiative (NNI) was proposed in 2000 aiming to advance research, development, and commercialization of nanotechnology, push for education and scientific literacy, and support responsible use (Sargent Jr., 2010; National Academies of Sciences, Engineering, and Medicine, 2020).

Since the creation of the NNI and similar initiatives, nanotechnology has quickly entered the mainstream through the components making up our everyday devices such as televisions, laptops, and smart phones. Through the exploration of nanotechnology in computing, the ceiling of innovation has been raised, leading advancement in quantum computing and ultra-small devices (Wu, Shen, Reinhardt, Szu, and Dong, 2013). Concurrently, nanotechnology has made an outstanding impact in medicine, particularly in cancer research towards therapies. Particularly, nanoparticles, quantum dots, carbon nanotubes, and other forms of nanotool have made significant contributions to the field
of cancer treatment. For example, multifunctional nanoparticles loaded with therapeutic drugs and imaging agents, and lined with biological response modifiers, are used to locate and image cancerous tissue, while providing treatment at the same time (Misra, Acharya, and Sahoo 2010). Use of nanoparticles for targeted drug delivery allows for highly precise, yet relatively non-invasive cancer treatment (Yih and Al-Fandi, 2006).

The atomic force microscope (AFM), invented as a follow up to the STM, is now a commonplace nanotechnological tool. A particularly exciting capability of the AFM is its ability to image at atomic resolution, having created detailed renderings of the topology of surface atoms soon after its invention, contributing greatly to materials science (Rugar and Hansma, 1990). The AFM also has the unique feature of being able to operate using a submerged sample, which has seen success in the investigation of mechanical properties of breast cancer cells (Ansardamavandi, Tafazzoli-Shadpour, Omidvar, and Jahanzad, 2016).

Nanotechnology has been explored and used in earth and climate sciences as well. For example, the study of nano-mineral properties for global heating and cooling, carbon-based nanofilms and their potential for electric conductivity, and nanoprecipitation within soil that may have implications towards toxin distribution have all greatly influenced the earth science field (Hochella, 2002). Responding to calls for eco-conscious practices, nanotechnology has been a driver towards revolutionizing agriculture to be more sustainable while being equally as productive through the use of engineered nanomaterials for improving crop growth (Lowry, Avellan and Gilbertson, 2019). In the search for environmentally friendly advanced energy systems, nanotechnology has also contributed to solar and fuel development (Zach, Hagglund, Chakarov, and Kasemo 2006). Nanotechnology, though useful in electronics, medicine, environmental sciences and life sciences, is not strictly limited to these fields. Research in NST is expected to lead technological innovation and result in positive effects on the global economy by introducing
less expensive research methods while simultaneously widening job prospects (Roco and Bainbridge, 2005).

Given the growing societal importance of nanoscience and nanotechnology, there is an established need for equipping the new generation of workforce with the scientific and technological knowhow of NST as well as generally scientifically informed and literate citizens (Friedersdorf, 2020).

### 2.3 NST in Education

NST’s rapid expansion as a multidisciplinary field has resulted in a continuous demand for skilled new generations of scientists, technicians, and engineers (Friedersdorf, 2020). In response, there is a call for NST-related content and experiences to be integrated into K-12 curriculums to introduce students to NST concepts and applications before entering higher education realms (Jones, Andre, Superfine, and Taylor, 2003; Kähkönen, Laherto, Lindell, and Tala, 2016). The demand has consequently prompted science educators and researchers to study frameworks for teaching NST, concepts to emphasize, and teacher professional development practices surrounding this content. However, NST, being a relatively newly emerging field, can be difficult to implement as an early learning experience (Blonder and Sakhnini, 2017; Friedersdorf, 2020). NST is often inaccessible to K-12 students and unfamiliar to K-12 teachers, due to its’ specialized, technological nature (Furlan, 2009). Most reported work focused on NST interventions is concentrated in undergraduate levels and upper high school grades (Stavrou et al., 2015; Blonder and Sakhini, 2017). Yet, there are reports that state the need for early interventions for their potential to positively impact students’ interest in STEM fields and careers (Stevens, Sutherland Krajcik, 2009; Greenberg, 2009).
2.3.1 NST concepts in the classroom

As a starting point, Stevens, Sutherland and Krajcik (2009) suggested a set of central ideas as a framework to draw from when introducing NST to grades 7-12: Size and Scale; Structure and Matter; Forces and Interactions; Quantum Effects; Size-Dependent Properties; Self-Assembly; Tools and Instruments; Models and Simulations; Science, Technology and Society. The identification and use of key NST ideas create a foundation for students to build upon their knowledge, and for teachers to easily revisit concepts and investigate student progress. The nine big ideas are meant to cover both fundamental scientific concepts as well as their applications, allowing students to develop skills necessary to move forward in NST (Stevens, et al., 2009). Many of the ideas overlap with Next Generation Science Standards crosscutting concepts, such as Scale, Proportion, and Quantity; Systems and System Models; and Structure and Function (NGSS, 2013). Similarly, Blonder and Sakhnini (2017) suggested insertion points within existing high school science curriculums where learning experiences encompassing NST ideas may fit in. For example, lessons on atomic structure in chemistry may be a place to incorporate the previously suggested big ideas of size dependent properties or size and scale. By naming points where NST can fit into existing curriculums, Blonder and Sakhnini highlight the interdisciplinary nature of NST.

2.3.2 Teaching of NST concepts

Though there are concrete suggestions for introducing NST to K-12 classrooms, implementations of NST range in their teaching methods and content focuses. A common theme between NST education studies for grades 7-12 is a hands-on approach, drawing on constructivist theories of learning. Many also make use of the AFM, often modeling or simulating its’ working principles. However, most experiences highlight use of
simulations and do not typically use the tool in real life. Pelleg and colleagues (2011) implemented a nanotechnology unit, in an elective introductory engineering class for all grades, at a science and engineering high school, focusing on size and scale, size dependent properties, and nanoscale characterization with a mix of lectures, short labs that modelled phenomena and tools, and finally allowed students to observe nanoparticles interact with DNA nucleotide bases. The unit was evaluated for its effectiveness through a word association survey, concluding that students were more likely to associate nanotechnology terms to science and engineering rather than media and consumer products after the unit. Stavrou, et. al., (2015) found that students gradually accepted that property changes are possible due to changes in size through engagement in a similar series of nano-lab activities. Jones et al., (2003) had grade 9 through 11 biology students remotely operate an AFM with a haptic interface, utilizing touch in an otherwise invisible context. This experience resulted in improved understanding about scale and dimensionality. Blonder and Sakhnini (2012), tried a variety of teaching methods to introduce size and scale and surface-area-to-volume ratio, a size-dependent property, including playing games, storytelling, multimedia, project-based learning, and modeling. Lati, et al., (2019) investigated student motivation to further study NST after activities exploring properties of a nanomaterial, silica aerogel. Even nanotechnology through the arts has been surveyed, by creating a set of activities that connect stained glass to the size-dependent properties of gold and silver nanoparticles (Duncan, et al., 2010).

Drawing from these empirical studies and the theoretical frameworks, the modules created as a part this study used a hands-on approach. However, one key difference is the way we brought and used an AFM, as well as a functional LEGO model, in the classroom, giving middle school students physical access to explore NST concepts through a nanotechnological tool they would otherwise not have access to. The LEGO AFM, in particular, contains the basic working components of the AFM for students to see, as a
real AFM’s components are hidden from view, and much smaller than the model. This technology- and application-based approach is meant to introduce students to the basic, big ideas of NST starting from a use of nanotechnology, drawing from the constructionist framework. This study is mainly focused on the use of the Model of Educational Reconstruction (MER) as a theoretical framework, which has not particularly been utilized in the context of application based NST learning.

2.3.3 NST and Teacher Preparation

Nanotechnology being as new as it is, and having the societal significance it does, implies a need for teachers to be comfortable integrating NST concepts in their classrooms. As NST continues to grow as a field, experiences cannot be limited to scientists visiting schools with expert NST knowledge; teachers being well prepared to teach NST can maintain a comfortable flow of learning. However, because of the novelty of NST, ways to prepare teachers to include NST in their curriculums are still actively being studied.

Shulman (1987) coined the idea of “pedagogical content knowledge” or PCK, where content knowledge about a topic and the pedagogy surrounding it intersect, making for a more effective learning experience for the students. Studies that attend to teachers in NST education suggest that building teachers’ PCK about NST is going to be critical to successfully implementing NST concepts (Huffman, et al., 2015; Stavrou, et al., 2018). Blonder (2010) found that exposure and practice with an AFM teaching model had a positive impact on teachers’ attitudes towards teaching NST and their content knowledge. Lee, Wu, Liu and Hsu (2006), similarly found that teachers with little knowledge about NST had improved their content knowledge and interest in NST after participating in a professional development experience. The studies suggest that given time and support, teachers can be well prepared to teach the novel NST concepts in their classrooms.
The instructor perspective plays a key role in using the MER as a framework to develop any learning experience for students (Duit, et al., 2012). In using the MER, teachers actively consider their audience and their needs to meet after clarifying the science content to be taught. Our participating teachers, although novice to the specific NST field, have considerable expertise in science teaching. As we bring the new content to the teachers, we account for their expertise in teaching, and understanding of student learning levels and needs at specific grade levels. Involving the teachers in the iterative MER process helps them align the pedagogy with the specific NST concepts. In doing so, the MER is meant to improve teachers’ PCK about a topic as a result. This study, by using MER as a framework, took into major consideration inputs from the collaborating teacher while designing and revising our modules. It also aims to share insights about the collaborating teacher’s perspective and attitude towards teaching NST after working on the modules.
CHAPTER 3

MODEL OF EDUCATIONAL RECONSTRUCTION

3.1 Overview

The Model of Educational Reconstruction (MER) was originally introduced in 1996, intending to bridge the gap between accepted scientific content and student understanding of the content (Kattmann, Duit, Gropengiesser, Komorek, 1996). The MER includes a cyclical process of constructing and reconstructing a particular scientific learning experience, using both scientific literature and real-life contexts to create a meaningful learning environment. The iterative process results in thorough content development, while structuring its implementation in response to student ideas and misconceptions, meanwhile positively impacting teachers’ pedagogical content knowledge (PCK). As a framework based in constructivism, MER was developed from a perspective that “assumes that there is no ‘true’ content structure of a particular content area” (Kattmann, et al., 1996, p. 2) and therefore, no one science content structure is the “correct” structure when designing lessons. Because of this assumption, equal emphasis is placed on both student ideas about the content as well as the accepted content structures within the scientific community. The MER includes three interconnected components that influence each other:

a) a clarification of the scientific content to be taught, including analysis of the educational significance of the content,
b) identifying students’ ideas and pre-requisite knowledge, and teachers’ perspectives on the subject, and attitudes towards the subject matter before instruction, and

c) the design and evaluation of learning environments, materials, resources, and activities in response to first two elements.

Continual evaluation of the lesson’s efficacy and student perspectives plays a large role in revising the learning experience towards making it more effective for teachers and students (Duit, et al., 2012). The following section discusses these overlapping components.

Figure 1: The three interconnected components of MER, as created by Duit and colleagues. From The Model of Educational Reconstruction — A Framework for Improving Teaching and Learning Science by Duit, et al., 2012, *Science education research and practice in Europe*, p. 21. Copyright 2012 by Brill Sense.
3.2 Components of the Model of Educational Reconstruction

3.2.1 Component A: Clarification and analysis of scientific content

The first component of the MER serves as the starting point for the cyclical process of constructing and reconstructing a lesson. When attending to this component, the focus is on review of the science content to be taught (Duit, et al., 2012). In doing so, both the accepted perceptions of a topic (i.e. relevant literature) and perceptions based on human experiences (i.e. contexts relevant to the learner) are considered. The main aim for this component is to find the “elementary” features of the content so that they can be clearly implemented in a content structure for instruction (Duit, et al., 2012).

First, one would consider science content structures that are already common in the representations of the subject matter. This includes commonly used textbooks, well known research journals, and other publications by experts of the topic. If the topic has a significant history in beliefs associated to it, a review of all previously held beliefs may be considered as well. For example, if one were planning to structure an astronomy lesson such as Earth’s orbit around the sun, one may want to include the historical development of beliefs surrounding this topic. The review would then include ideas such as the Earth-centric point of views held by Plato in 4th century BC (Lawson, 2004) to the current, accepted understanding that the sun is the center of our solar system and the Earth orbits around it (Koestler, 1989). In completing such a review, one is exposed to former and presently existing representations of that topic and builds upon their own content knowledge of it.

The second aspect of this component is to acknowledge the educational significance of the topic. The goal of this is to tailor the content to the audience, establish a context for the lesson planning and ultimately aid in the transition from science literature to content for instruction. This process decides which content to prioritize. Much of
the literature on any given scientific topic is written for other scientists, researchers, and experts in that field. Duit, et al. (2012) suggest that in reviewing the content, it is crucial to approach the literature from a science education perspective, and potentially include review of science education practices in the subject being examined. By considering both the content at hand and the pedagogical knowledge surrounding the topic, teachers can broaden their content specific pedagogical knowledge, introduced by Shulman (1987).

Figure 2: The processes of science content clarification and educational significance analysis, as created by Duit and colleagues. From The Model of Educational Reconstruction — A Framework for Improving Teaching and Learning Science by Duit, et al., 2012, *Science education research and practice in Europe*, p. 21. Copyright 2012 by Brill Sense.
3.2.2 Component B: Identification of student perspectives, analysis of teaching and learning

Consideration of the audience and context lends itself to surveying student beliefs about the topic. Component B includes clarification of the science content and a consideration of the education aspect. To make scientific content easily accessible for K-12 students, it is important to consider not only the scientific literature, or the pedagogical literature, but also students’ preconceptions, exiting knowledge, and attitudes based on their everyday lives and experiences. Framing science content in a context that the students are familiar with can make the learning experience more interesting and accessible. The prior knowledge students have is also useful to shape lesson objectives. For example, middle school students do not necessarily have a full and scientifically accurate perspective on physics concepts.

However, students may have a set of preconceived notions about some concepts. Ideas around force, motion, energy being to take shape early, when students encounter these words even outside classroom in everyday environments. For example, one idea a student may have about the force of Earth’s gravity on objects is that weight increases as objects are lifted higher off the ground. An idea like this may come from lore about pennies thrown off the Empire State Building injuring pedestrians below, a tale many have heard casually. Though an object’s weight in Newtons is constant on Earth, this is not necessarily an argument to discredit, and instead is a preconception to consider when planning a lesson to better guide the student towards understanding the physics concepts behind weight and gravitational potential energy (Driver, Guesne, Tiberghien, 1985). Alongside student ideas about scientific concepts, perceptions students have towards themselves, and their attitudes towards the topic can serve as starting points in lesson planning. Student attitudes towards the subject may be a useful metric of engagement as
well. For this component, Duit and colleagues recommend qualitative analysis methods such as interviews or miniature lessons to directly survey the preconceptions students hold about the subject matter.

3.2.3 Component C: Design and evaluation of learning environment

Finally, the MER’s third component is at the core of the framework. It focuses on the design, implementation, and evaluation of the learning environment. After reviewing the science content literature, pedagogical literature and research, and accounting for students’ perspectives, a lesson or study directly influenced by the results of Components A and B is created. Then, the lesson or study would be implemented and evaluated throughout. During the continuous evaluation, the focus is still on Components A and B, examining how the scientific content is being presented in instruction and taking note of students’ ideas throughout, as well as considering their own self-beliefs or attitudes. During implementation, the aim is to identify student misconceptions and areas of difficulty, which can further help revise the learning experience.

All of these aspects are to be given equal consideration when beginning the recursive process of the MER. Following evaluation of the lesson’s effectiveness, updated student ideas including areas students struggled, and the teaching experience, the lesson or study may be revised and reimplemented to make it stronger. Each component is influenced equally by the other two and vice versa. The MER is naturally a cyclic model, where each component builds upon itself in real time. The process of reviewing Components A and B, and revising the plans for the experience, is repeated until the learning experience is satisfactory, continuing to tailor to the students’ and teachers’ needs throughout.
3.3 Applications of the MER Framework

The MER has been employed in designing and evaluating a wide range of science education topics in many grade levels, particularly undergraduate physics. For example, Saarelainen and Hirvonen (2009) proposed using the MER in planning electromagnetism lessons, specifically to create teaching sequences for electrostatics. Electromagnetism is typically too abstract for students to understand quickly. Saarelainen and Hirvonen found that using the MER as a framework to teach concepts such as forces generated by an electric field was effective in improving student understanding when comparing exam scores from before and after following the teaching sequence. Levrini (1999) described pathways to teach undergraduate modern physics based on clarification of content and educational significance of spacetime. Taking into account both the scientific content and where students frequently struggle, Levrini’s research suggested the design of a lesson aiming to answer questions students may have along the way. Saarelainen and Viiri (1999) provided insight on student understanding of optics through their study employing MER in university optics lessons. Their early study aimed to point out gaps in conceptual understanding of light and seeing, concluding that polarized light is a concept that students struggle with, suggesting a focus on this gap in the next iteration of the lesson. Studies of the MER in physics occur for the high school level as well. For example, Kersting, Henriksen, Bøe, and Angell (2018) used the MER to design and evaluate an advanced general relativity lesson for final year high school students. The study used student interviews and written responses to shape the lesson as it continued. Kersting and colleagues found that when given appropriate time and scaffolds based on their learning needs and levels, the participating students showed improved understanding of underlying physics concepts.
The MER has shown to be useful in a wide range of science domains. For example, Reinfried and colleagues (2015) employed the MER for physical geography, with the aim to help middle school students to develop their conceptions about water springs and to understand counterintuitive aspects when comparing two different types of springs. Their findings demonstrated successful and stable gains in student understanding. Reinfried and colleagues noted the short duration (90 minutes) of their intervention, suggesting that the MER is effective over brief periods of time. This result suggests the MER can be useful for informing short module development. Similarly, Felzmann (2017) utilized the MER to examine early high school student ideas of glacier formation and ice ages. Results from the study suggested that the of MER helped identify areas of difficulty for students learning of the topic. Felzmann also suggested that the MER helped turn the complicated geoscience concepts into less complex, teachable, core ideas. The MER has also been used in the context of climate change. Niebert and Gropengiesser (2013) used the MER to develop a learning environment for late high school students wherein students preconceived notions of greenhouses gases and their effects on the planet are explored. Continuous evaluation of the designed learning environment resulted in being able to track the learning paths students took towards developing their understanding about climate change.

The MER framework has informed the design of learning experiences in computer science (Diethelm, Hubwieser, Klaus, 2012; Grillenberger, Przybylla, Romeike, 2016), life sciences (Riemeier Gropengiesser, 2008), and electrical engineering (Block, 2016). Stavrou, et al., (2015) utilized the MER in an NST context, developing a learning sequence for eighth grade students, introducing the big idea of size and scale. Stavrou, Michailidi Sgouros, (2018) also studied teachers’ perspectives on teaching and learning NST by using the MER themselves to create a teaching-learning-sequence. Among these studies, the MER has shown to be useful to enhance students’ learning of difficult
or new concepts, due to its’ reflective and recursive nature. The emphasis on student ideas and teacher perspective makes for an experience that is more contextually relevant and meaningful.

### 3.4 Use of MER in this study

Insights from the above listed empirical studies guided use of MER for this study. The MER was chosen for design, evaluation, and revision of the NST module, because the MER has shown to be successful in introducing students to typically difficult or abstract concepts in the physical sciences. Therefore, the MER framework may be a good fit for creating NST learning experiences for K-12. The MER also allows for tracking of student engagement and content understanding through participation in the revision process. In the study, the recursive process began with a clarification of the relevant science content via textbooks and other publications from experts in the field (Component 1). This included review of accepted definitions relevant to NST and current advancements in the field for a complete picture of the field from a scientific perspective. Then, in order to review the content with a science education lens, an analysis on NST education literature was conducted. In doing so, content structures used to present NST to students can be studied to influence lesson planning.

For the study, we intended on introducing students to NST concepts via the atomic force microscope (AFM). The AFM, a commonplace NST tool, can image sample surfaces at the nanoscale. However, the details of the AFM’s working principles are beyond the typical scope of eighth grade physics understanding. The AFM works by sensing small Van der Waals forces between its’ tip that scans over the sample surface, and the sample (Giessibl, 2003). The tip either taps or hovers above the sample, and a laser/detection subsystem measures any changes in the tip height due to the interaction
forces. These forces are naturally-occurring between any two atoms, molecules, or surfaces. We did not insist that students understand these forces, but we did focus on the sub-systems and their roles in producing an image. Regardless, the AFM is a "black box" with its sub-systems being very small, and hidden from user view. Hence, we developed a LEGO AFM model (Figure 4), that includes the moving sub-systems: the cantilever/tip, and the laser/detector. The model enlarges the hidden inner working systems of a real life AFM (Figure 3), making the image production process visible to the students.

Figure 3: The real-life AFM we used in demonstrations and as inspiration for the LEGO model. The AFM’s total dimensions are approximately 12 inches x 12 inches x 6 inches, with the actual microscope components being hidden from user view, and much smaller.

Inputs from high school science teachers, such as concepts students were already familiar with and implementation of the science standards (NGSS Lead States, 2013), were considered to inform module design and instructional practices. These discussions also aided in identifying the teaching context.
By studying NST from an educational perspective and taking inputs from current science teachers, the audience’s point of view is considered (Component 2) and the lesson can better attend to student needs. The content review and perspectives from teachers informed the development of a pilot nanotechnology module wherein students were introduced to nanoscience and nanotechnology through the AFM. Investigation of the results of the pilot module, including responses student reflections and attitude surveys, led to revisions towards improving the learning experience and implementing a reworked module (Component 3). The reworked module was then used to probe students’ readiness to explore NST, attitude towards learning the NST concepts, aspects that support understanding and conceptual difficulties they faced. Though only two rounds of implementation have occurred so far, as the MER is a continual cyclical process, the results from the revised module may now be used to revise again and continue the recursive process of the MER, strengthening the learning experience with each revision. In the following chapter, I will discuss the use of MER to develop the module for this study in further detail.
CHAPTER 4

MODULE DEVELOPMENT

In this chapter, I describe the ways in which MER was utilized during the study, and how we leveraged the interconnected components towards creating application-based, technology rich NST modules for grade 8.

4.1 Participants

The participants included teachers and students from two public school districts in Massachusetts. The initial teacher discussions and introductory lesson were held at one of the school sites with 4 teachers and 45 students from grade 8 and 9 science courses. The pilot module was held at a middle school from a second school district with 77 students across four eighth grade general science classes, and with a collaborating science teacher. The revised module was held at the same school, where we continued to work with the same teacher, with 47 new eighth grade students. Data was collected and used from students who consented for the study.

4.2 Preliminary Sessions

The MER calls for a clarification of the scientific content to be taught, as well as the context for the module (Component A). Before planning the module, the research team
reviewed current NST literature and identified scientific content that would be appropriate to be introduced in high school. Following this, an initial set of discussions with collaborating high school teachers were held to better identify appropriate curricular alignment for introducing NST concepts at the early high school level. These discussions with different school faculties from physics, life sciences, chemistry, and engineering helped us find curricular alignment (relevant standards) as well as grade-appropriate context for introducing the content. Teacher inputs were crucial to best structure the lessons and decide upon facilitation techniques, and in doing so, listening to their perspectives attended to the second component of MER (Component B). During these discussions, an overview of NST concepts and the intended approach of using technology, specifically the AFM, to introduce the new NST concepts to students was presented to the teachers. The teachers then made suggestions for topics where NST could be introduced and alignment with the current science standards (NGSS, 2013). For example, the engineering teacher agreed with using the technology-based approach. The teacher saw value in introducing students to a new technology and its exploration, and also suggested an overlap between the NST content introduction and newly introduced engineering standards. The collaborating chemistry teacher identified places within the curriculum to introduce nanotools to help students apply chemistry content. There was an overall consensus that an NST module for early high school may have significant impacts, despite the field’s novelty. The application-based learning format was formalized out of the discussions, and a short, basic lesson was created, finally attending to Component C: design and evaluation of a learning experience. The introductory lesson featured a functional LEGO model of the tool, AFM (Figure 4). The model included the physical LEGO component, demonstrating the movement of parts inside an AFM, and a computer interface that students watched create an image of the ‘sample’ surface on the LEGO component. A demonstration of the LEGO AFM fol-
lowed by a slideshow presentation defining nanotechnology and introducing some of its applications was held for two grade 8 and one grade 9 class. The lesson was intended to gauge student engagement with NST concepts, that would help us understand their perceptions and readiness to engage in learning NST. The lesson was facilitated by the research team and conducted for 45 minutes. After the lesson, students were given a survey asking what appealed to them the most, with the response largely being about the LEGO aspect of the AFM model. In discussions following the introductory lesson, the teachers met with the researchers to share their inputs and to examine survey results. Teachers expressed excitement towards the LEGO AFM, suggesting it was an effective teaching tool. The teachers thought the LEGOAs were relatable and familiar to students, making the scientific concepts more approachable and less mysterious. Therefore, a main input among the teachers was to keep the LEGO AFM. The teachers suggested building on the image analysis aspect of the AFM in further additions to the module, to help students to understand the application of AFM. This might include examining the phase shift graphs associated to the images, as students could apply their knowledge of analyzing plots and graphs. Standards and curricula were again reviewed, now having seen the module, to find places where specific explorations using the AFM and its image analysis abilities could be used to introduce a topic within a discipline and connect back to nanotechnology. Notably, the chemistry teacher suggested using the LEGO AFM to study polymers, directly connecting to existing chemistry labs. These suggestions were carefully taken into consideration to create a complete pilot module. Design of the pilot module would then be the beginning of the next cycle of MER, as it drew from the results of the introductory discussions and lesson, to evaluate the learning experience and strengthen it with the next iteration. The pilot module design and revisions based on its implementation are discussed in the following section.
4.3 Pilot Module

The pilot module was designed with the aforementioned inputs in mind, with the help of the collaborating teachers from the introductory sessions. The module was taught mainly by the researchers with support from one new collaborating teacher and implemented across four new grade 8 classes. Reflection questions students were asked are discussed in the following chapter. The pilot module used the 5E model (Bybee, et al., 2006) as the lesson planning framework. The 5E model, in particular, was chosen for its’ constructivist approach (Duran Duran, 2004). 5E is a common framework used for emphasis on student engagement, where the first step is to grab the students’ attention, and by the end evaluate what they have learned. The pilot module was designed to have two parts, introducing students to a common NST tool, the atomic force microscope (AFM). The first part focused on the LEGO AFM. A researcher led a ten-minute pre-
Figure 5: From left to right, three separate student models of the LEGO AFM from the pilot module. All student models included the main required components: the cantilever, the tip, the laser, and the sensor.

The presentation on the nanoscale and discussed the AFM as a necessary tool to observe at the nanoscale, before moving onto the ten minute LEGO AFM demonstration. After students watched the LEGO AFM run, they answered content probing questions about the LEGO AFM in groups of four, for about five minutes. Then, for fifteen minutes, they created their own models of an AFM with materials such as cardboard, popsicle sticks, glue guns and pipe cleaners (Figure 5). Students were given few criteria, and were only required to include the four main components of the AFM: the cantilever, the tip, the laser, and the laser sensor. The modeling task was proposed by the collaborating teacher,
to explore the parts of an AFM in a hands-on way. At the end of the first part, students individually completed an exit ticket asking if they found the LEGO AFM model useful in understanding how the AFM works.

In the second part of the pilot module, a real AFM was brought into the classroom, and was used to study polymer structures at the nanoscale. Students were asked to consider why a clear plastic cup breaks less easily than a Styrofoam cup. Then, students were given a cup of each type and tasked with a “destruction test” to observe what happens when they try to break the cups, finding Styrofoam to be brittle and plastic to be flexible. Next, the real AFM scanned and produced an image of the polymer that made up the plastic cup they had just tried to destroy. Students were asked to observe the image, and study a phase shift graph, denoting harder and softer spots in the sample. To further understand the phase shift graph, students worked together in groups to recreate a phase shift graph by graphing the scanning movement of one student’s finger over a bumpy surface (Figures 6,7). Finally, the image of the plastic cup polymer
Figure 7: Student drawn phase shift graph, noting hardness and softness of the material being modeled (a bumpy clay surface). This example also considers the height changes of the surface.

was compared to an image of the Styrofoam, and the image analysis of differences between the cups answered the original investigation question. These activities were followed by a whole class discussion to unpack the connection between the imaging process explored during the first part, and the resulting image and its analysis. Finally, students individually answered questions about the purpose of an AFM image as another exit ticket activity. Students were also given a modified version of the S-STEM survey (The Friday Institute, 2012) before and after the module. The S-STEM Surveys\(^1\) asked students to rate their interest in STEM subjects (math, science, engineering/technology) and eleven STEM career fields. STEM subject questions were statements such as, “math has been my worst subject,” or “I am sure I could do good work in science.”

\(^1\)Full details of development and validity of the S-STEM Surveys are available via The Friday Institute at the North Carolina State University.
respond on a scale from 1 (strongly disagree) to 5 (strongly agree). Similarly, students read descriptions of career fields like physics, chemistry, medicine, etc. and rank how interested they are in the field from 1 (not at all interested) to 5 (very interested). Finally, students respond to yes or no questions about their interest in taking advanced STEM classes and whether they know anyone who works in STEM. All questions from the surveys can be found in Appendix A.

As the MER is a cyclical process, and all components should be addressed throughout, design, implementation, and evaluation of the pilot module continually drew from the framework. Teacher perspectives on the content and the learning environment were considered in module design. The pilot module plan was influenced both by the teacher inputs from the introductory sessions as well as the collaborating science teacher, who gave suggestions for activities based on experiences with her classes. For example, she suggested a modeling task, having seen the benefit of students exploring something unfamiliar through modeling before. Student ideas about the content, and their perspectives towards NST were investigated during the module as well. Themes within responses from students’ individual reflections suggested that students needed more time breaking down the AFM as a tool before delving into image analysis. Students were sometimes able to identify certain sub-systems, but not how they worked together to produce an image. When asked how the AFM was useful in seeing the differences between two cups, many students described the images they saw without reasoning or connection to the imaging process. Therefore, a clear conclusion from the pilot module was that a thorough understanding of the imaging process is necessary to effectively perform image analysis. After evaluation, the pilot module was revised again to better support the students in understanding the imaging process of the AFM.
4.4 Revisions to Pilot Module

The revised module only focused on the first part of the pilot – the LEGO AFM exploration – in response to evaluation of the pilot module. The intent of slowing down the module was to allow students the time and resources to investigate the AFM’s working mechanisms, its underlying physics principles, each of its subsystems, and how those subsystems contribute to the imaging process. Hence, the revised module also included multiple deliberate experiences with the AFM. The revised module included both the LEGO AFM demonstration and the modeling task from the pilot module. However, a reading task about the history of AFM was added to further give students context surrounding the AFM and its use. A demonstration in which students were shown a laser pointer and a mirror, one of which had a changing angle, was added as well, to break down the laser component of the AFM. Finally, students were given an exit ticket to reflect upon the usefulness of the LEGO AFM, the purpose of a real AFM, and how they would be connected. Students were also given the S-STEM surveys before and after the revised module, though they now included a content questionnaire. The content
Figure 9: Students test their AFM model by shining a laser on their cantilever’s reflective surface, to check for deflection towards sensors.

The questionnaire included two multiple choice questions about the meaning of the prefix nano- and one open-ended question about the importance of nanotechnology. Implementation of the revised module was also teacher-led rather than being researcher-led, as in the pilot module. Following the module, we held a short interview with the teacher to reflect on her preparedness to teach the module and introduce NST concepts into the classroom.

Though the revised module was the last iteration of the MER cycle for this particular learning experience, observations from the process of designing, implementing and evaluating the revised module can be used to further strengthen it if desired. Student ideas about the content were observed via classroom videos, and their responses to their exit tickets and content questionnaires. For example, it was difficult to tell whether students realized the difference between imaging at the nanoscale and imaging a nano-sized object. This is a conception that could be further explored in another round of revision. This iteration of the module also had an emphasis on the teacher perspective.
The revised module was teacher led, allowing the teacher to experience firsthand the student response to NST and explore her readiness to teach NST concepts. The teacher was asked to reflect upon her experience at the end of the module as well.
CHAPTER 5

RESULTS AND DISCUSSION

In this chapter, I present results from data collected during the modules and discuss what the results tell us about student engagement with technology-heavy, application-based NST modules for grade 8. Throughout this study, our intent was to explore student ideas about NST based on their participation. Therefore, I review the evolution of student ideas over the course of module revisions. Then, I discuss the impact of participating in module development and implementation on the collaborating teachers’ preparedness to teach an NST module. Figure 10 demonstrates a condensed version of the study structure, and how data sources align.

5.1 Results

5.1.1 S-STEM Surveys

One goal of the study was to investigate student attitudes towards STEM and interest in pursuing STEM in the future. To do this, students were given S-STEM surveys (The Friday Institute, 2012). Student responses to Likert-scale questions were assigned numbers where 1 = Strongly Disagree, and 5 = Strongly Agree. The numerical data was then compiled to compare pre- and post-module ratings from all participating students, using paired t-test analysis (Roberson, Shema, Mundfrom, Holmes, 1995) Frequency of answers were counted for the final yes or no questions. Results of the S-STEM surveys
Figure 10: Chart of obtained data sources, and how they combine to inform answers to our research questions.

for both the pilot and the revised module are shared below. Note that the modules are too short in duration to infer any direct claims about the influence of the module on students’ attitudes. Still, evaluation of the student perspective remains a large part of the MER process, and therefore have been used to inform module development. The surveys also allow us to examine potential areas of interest the students have that NST could expose them to. The full S-STEM Surveys can be found in Appendix A.

Pilot Module: Analysis of S-STEM surveys from the pilot module found no statistically significant change in pre- and post-attitudes towards STEM subjects, $t(2) = 1.76, p = 0.2$. Though average attitude scores increased slightly for both science and engineering/technology. Similarly, the surveys found no significant change in interest towards STEM careers, $t(10) = 0.96, p = 0.3$. However, we saw increases in math, computer science, engineering, medical sciences and medicine, which are disciplines that are rel-
relevant to NST. It is possible the pilot module had influence on the students’ interest in working with math, having done a phase shift graphing activity during the module. The surveys did not find strong statistically significant changes in number of students who have interest in taking advanced math, \( t(3) = 2.44, p = 0.09 \), and science courses, \( t(3) = 1.98, p = 0.2 \), in the future. However, both subjects demonstrated an increase in number of students who said they would take advanced STEM courses, suggesting potential influence in their interest in pursuing advanced STEM topics after exposure to the NST module. While no direct claims were made from these results, these results informed us about students’ background and consequently, their perceptions surrounding STEM as they apply to NST. The results suggest that students may have been intrigued by the NST content, and it may have positive influence on STEM perceptions and attitudes if students were to continue with NST-related content.

Revised module: Similarly, the S-STEM survey results did not demonstrate statistically significant changes in pre- and post- attitudes towards STEM subjects, \( t(2) = 1.35, p = 0.3 \), and interests in STEM careers, \( t(10) = 1.99, p = 0.07 \), and advanced math and science courses, \( t(3) = 3.0, p = 0.06 \). Nonetheless, surveys from the revised module showed an increase in all three subjects students rated (math, science, and engineering/technology). This was a positive change from the pilot modules, which had nearly stagnant results between pre- and post- attitude values. The surveys also showed increases in more STEM career fields than previously, with increases in nine out of eleven career fields, as compared to five out of eleven in the pilot module (Table 1).

For example, in this round, we found that Earth Science shows a large positive increase. This increased interest may be due to some specific module related experiences. During the AFM module, students studied topographical images of the sample scanned using AFM. During a discussion on topography, and different types of studies that focus on topography of surfaces, the teacher, used an explicit example of study of ocean
Table 1: Changes in student self-reported attitudes towards STEM career fields from 2019 to 2020. Scores were collected from a Likert scale survey where 1 = Strongly Disagree and 5 = Strongly Agree. Attitude scores were averaged across all classes.

floors. The use of this specific example may have had some influence of students thinking about the use of AFM or reason for topographical studies. Some students referred to the scanned sample surface as the ‘ground’, in their reflections. It is possible that in doing the post-surveys, students related with the teacher example of ocean surface and made a connection with Earth science field. While we do not have direct evidence apart from student reflections, based on literature on the impact of teacher examples or metaphors in student thinking, we may argue for a potential influence of teacher explanation to student response. We also found increased interest in the career fields
of Veterinary and Medicine. This might be possible because of the multiple examples given around use of nanotechnology is detection of medical ailments, drug delivery and finding cures, especially for cancer.

Results from surveys, although they did not show any statistically significant changes, reflected positive increase in STEM attitudes amongst the students. We acknowledge that the sample sizes, particularly for the revised module, are small \((N \leq 30)\) due to a number of students not filling out either the pre- or post-S-STEM survey. Because of the small sample size, variances in measurement can highly influence results (Delice, 2010). We note our sample size, and short duration of module implementations as limitations, discussed further in the concluding chapter. The positive changes in attitudes and interests towards STEM between the pilot and revised module may indicate a link between using MER to continuously revise a learning experience to improve it. MER aims to thoroughly take the learning context into consideration when planning a lesson. Because of this, students’ needs, and learning abilities may be better attended to when using MER to evaluate a lesson repeatedly. It is possible that if students are better engaged with NST content or enjoying the module’s experiences, they may find themselves more intrigued to pursue it further or feel confident about the topic. If that is the case, then giving extra support around students’ pre-existing ideas about NST may be useful in influencing student interest in NST careers in the future. As the demand for a skilled and scientifically literate workforce increases, engaging students with NST early may positively contribute to their awareness of NST and pique their interest to study it further.

5.1.2 Student Reflections

Throughout both the pilot module and revised module, students were asked to respond to reflection questions either individually or as a group. Responses to these reflection
questions gave insight into students’ thinking about NST content, and how the module impacted their understanding of the relevant concepts. In this section, student reflection tasks and their results are discussed, in attempt to answer our first two research questions. All reflections were studied using a broad thematic analysis (Braun and Clarke, 2012), in which we looked for common threads between student responses, regardless of scientific accuracy. The methodology of applying thematic analysis is described further in this section. The content questionnaire and all reflection questions can be found in Appendices B and D.

**Pilot module:** During class, students were asked to discuss and record answers to content probing questions in groups of four: 1) How does the AFM image the surface? 2) To image something very small, how should the LEGO AFM be changed? 3) What are some problems with the LEGO model? We analyzed the frequency of different types of responses to each question. We were not insistent that responses necessarily be scientifically correct or use particular vocabulary.

When asked about the imaging process, the majority of student responses focused on the general movement of the LEGO system. For example, “The AFM images the surface by going up and down.” It is important to note that the AFM is a complex system where different subsystems work synchronously. For students observing these systems for the first time, it might be difficult to recognize all the subsystems. An equal number of responses highlight the deflecting laser movements and the sensor system that captures the movements. However, such responses do not elaborate how these systems contribute to the image production. Although they did not provide any reasoning, we noted that some students started to notice the subsystems and their functions. Few responses focused on the cantilever movement, that is coupled with the platform movement, which helps scan the surface that is to be imaged. These responses recognized multiple subsystems. Although there was no explicit explanation of how the subsystems work together, stu-
Students recognized the different subsystems. The next question focused on the scale and asked for changes to the LEGO model to capture images at a nanoscale. The students had so far not seen a real AFM. Students mainly suggested scaling down the laser and sensor system, adding more sensors, and using stronger lasers. The next most frequent responses suggested reducing the AFM size but did not say how. A small number of responses suggested making a finer scanning tip to capture smaller scale without elaboration on how a finer tip helps scan at a smaller scale. The overall response trends suggest that students were thinking of the function of each mechanical element of the AFM and the scale to achieve magnification. The final question probed for potential problems with the LEGO system to see how students analyze technology with respect to its scale, purpose, and functionality. A majority of responses stated that the use of LEGO makes the model AFM fragile. Some stated the cantilever tip scratching the surface being imaged can harm the object affecting the image quality. A few responses listed potential inaccuracies within the system, like displacement of the laser from its position due to movements of other system parts. These highlight students’ increasing awareness of the scale and stability problems associated with the use of LEGO. They made attempts to analyze technology to see how well its ready to serve specific functions.

At the end of the module, students individually responded to the question, “Did the AFM help you understand the differences in the physical properties of the two cups? How?” The reflections were qualitatively analyzed using thematic analysis (Braun and Clarke, 2012). First two researchers independently sorted the responses as they looked for over-arching themes, consolidating into one set for the nature of the responses, focusing less on correctness or scientific accuracy. Sorting categories emerged out of the recurring themes. Next, responses from all the classrooms were de-identifying and ran-
domly mixed to create a master sheet for analysis. Three consecutive rating rounds by two other raters led to achieving an inter-rater reliability of 90%.

Most student responses only acknowledged the difference between the two cups without further reasoning. This may suggest that either the students failed to understand the question, do not attend to it completely, or the module has not helped them understand the function of AFM. For the next most frequent category, students described the image as they saw it, without elaborating on why or what it may mean, providing no analysis of the image. Although there is no evidence of students understanding of the related NST concepts, they were trying to achieve the next level in building scientific explanations going beyond rephrasing the questions. This may suggest that students still need support constructing and writing scientific explanations.

The next most frequent categories had equal responses that describe the purpose of AFM, which may suggest that the students were able to grasp the idea of scale and use of technology to attain zoomed in images. Also, responses that described how the AFM helps image the samples may reflect students’ understanding of the purpose of AFM as a tool and its function. Responses that not only described the differences in the cups, but connected back to the imaging process, might have exhibited a deeper level of understanding where they attempt to use the image as evidence and provide reasoning for why the cups exhibit certain properties. These responses ranged in levels of understanding either the question, the working properties of the AFM, or construction of scientific explanations. Our study design did not allow us to make any direct claims about the gains of the intervention at this stage. However, a small but definite number of reflections may suggest that students are ready to explore NST concepts and ideas that are beyond the prescribed scope of beginning high school study. These results informed revisions of the pilot module, suggesting students likely needed more time to explore the
relevant conceptual content surrounding the tool at hand, to develop their understanding of the imaging process further.

*Revised module:* The questions students were asked to gauge their understanding and ideas surrounding NST were updated to fit with the narrower focus of the revised module. At the end of class, students were given an exit sheet with three prompts. We wanted to understand if and how the LEGO model helped build understanding of the AFM, its’ function and its’ purpose AFM as a tool. Student responses were qualitatively studied to find in what ways the designed module supported student engagement.

The first question, “In what ways was the LEGO AFM model helpful in understanding how an AFM works?? probed students understanding about the usefulness of the LEGO model.

One major group of student responses indicated how the model helped students generally. Student responses indicated that they appreciated the accessibility of the model, the ability of the model to show them the different components and the working mechanisms of the tool. One student response in this category included, “the model was kid-friendly and helped me and visualize the real thing (AFM).” The second group of student responses informed us of their understanding of the model itself. Student responses in this group elaborated on the specific subsystem/s (either the cantilever/needle subsystem or the laser/mirror subsystem, or both). These responses suggest that the LEGO model helped students see and identify the individual sub systems of the AFM. Overall, an AFM is a complex system where just looking at it and its working, is not enough to understand its working and functionality. Although the LEGO model is a prototype that could not work at the nanoscale, it mimics the AFM’s working principles, highlights the subsystems, and shows how they work together. Therefore, using a scaled-up version of the AFM appears to be useful in unpacking how the tool works, and allows students to get comfortable with a piece of technology that is otherwise inaccessible to them.
The second question, “Reflect on the usefulness of the AFM. What is the purpose of an AFM?” probed student ideas about the purpose or use of the AFM as a tool. Most students mentioned measuring objects at the nanoscale, suggesting that this is generally what students believe to be the purpose of an AFM. It is a generalized view and did not include any specifics about the properties that could be measured. Another category of student response talked about topographical properties, some specifically mentioning the “height of the ground” or “heights of surfaces.” We found this to be particularly interesting because this points to the potential teacher influence on students’ framing of their response. For instance, while talking about the ability of AFM to scan surfaces, the teacher used a metaphor of ocean floor and scanning its’ “bumpy” surface for study by scientists. Influence of these metaphors was reflected in ways students mentioned “the ground” as the object they would study with an AFM. Analogies help learners imagine new information and hence, in science support the development of new ideas about something (Duit, 1991). Because the NST content was new, there may be the possibility of student explanations being influenced by the metaphors used in class. A small, yet definite number of responses also indicated potential confusion. Since most responses specifically talked about measuring at the nanoscale, it was difficult to tell whether students realized that there is a difference between measuring topographical properties of a sample at a nanoscale of a large object, versus just seeing the small objects. This may suggest a misconception that students may have about scale, or what the AFM observes.

The third question asked, “If we want to image something even smaller, something at the actual nanoscale, how do we change the LEGO AFM?” The purpose of this question was to see if students were able to connect the scaled-up LEGO model to the real AFM. The overall trend among student responses was on making the entire system smaller. We noted that most students who elaborated further, chose to point to the cantilever
tip/needle and indicated the need to reduce its size, to scan smaller objects. For example, students wrote, “make the needle more precise” and, “you make the needle smaller.” This may suggest that students saw the cantilever tip as the only point of contact between the sample and the tool. Therefore, they decided to focus on reducing the size of that component. They may have made the connection that a smaller sample will require more precision, thereby requiring a better tip. These responses suggest that students were aware of the scale and size of the model.

Finally, in the revised module, a content-based questionnaire that was administered before and after the module, included one descriptive question: Why do you think Nanotechnology is important? and two multiple-choice (MC) questions focusing on concepts of size and scale. We qualitatively analyzed student response to the descriptive question, using thematic analysis (Braun and Clarke, 2012) and analyzed frequency of accurate responses to the MC questions (Nowell, et al., 2017).

For the pre-questionnaire, most student responses to the descriptive question read, “I don’t know” or indicated similar responses reflecting an uncertainty in their thinking. The majority of the rest of the responses listed another field like medicine where Nanotechnology helped, highlighting application of NST. Further, only a small percentage of responses included specific details around how NST contributes to specific fields like medicine (example: by finding new cures). This category of response suggested that students had some background ideas about NST and its application to other fields.

For the post module responses, a significant change in nature of student response to the descriptive question was observed. More than three-quarters of the student responses included a general statement about size or scale of objects in focus for NST and that the nano scale itself imparts value of this field. A few students gave specific examples to talk about the importance of NST. For example, one student’s pre-module answer was a vague statement about innovation. Their post-module answer was, ‘It allows us
to see things at an extremely small scale, for example, a table that may seem smooth to us, a tool such as an AFM would be able to pick up small blemishes and imperfections in the table.’ Responses like these were not only able to describe the basic idea behind nanoscience (extremely small scale), but also the impact of the tool they were introduced to and what the tool does. Responses that demonstrated these connections suggest that with support, students were able to identify with the purpose and hence the value of AFM, as an important piece if NST technology.

We found that for a few students who reflected basic understanding of NST even before the module, post the module, reflected deeper understanding. For example, a pre-module student response, “Nanotechnology can help us in many ways including: surgery, medical diagnosis and treatment, engineering, science, etc.”, for post-module response said, “Nanotech can help improve things such as healthcare and things in the medical field, or in science and physics to study things that are very small. And so help in diagnosis or treatment effectively.’ While this student continued to relate nanotechnology to medicine, they also added the concept of size and scale, key ideas of NST (Stevens, et al., 2009) that play an essential role in the medical field. Although few, examples like these highlighted the role of the module and its structure, where our intention was to engage students with tools to build upon their ideas (Papert, 1980). The post module responses included a lot of examples from the medicine field. There may be a potential that the module helped students with background knowledge, to build their understanding of NST and its connections with medicine field. If students related nanoscience experiences to the field of medicine, they might see themselves working in medicine in the future. This could be also linked to the increased interest in the medicine field reflected in the post S-STEM survey. For the multiple-choice questions, we also found an increase in accuracy of answers. Although not statistically significant, the response showed a positive change. The non-significant difference may be because the
students did not have enough time to internalize the new ideas. This may also be related to the short module duration, which may be a limitation of our study.

5.1.3 Classroom Videos

Throughout the study, we took audio and video recordings where possible. During both the pilot and revised modules, videos captured whole class discussions and small group work, where students were building models, discussed them with their peers, and shared their builds to the class. As we studied the transcripts, we focused on student ideas and moments of sense-making as they engaged in group or whole class discussions.

We mainly studied how students engaged with the modeling task, which required the students to make non-functioning prototypes of the AFM using given materials: cardboard, modeling clay, pipe cleaners, toothpicks and popsicle sticks. The only design requirement for the model was to highlight the different components of the LEGO AFM (the cantilever, the platform, the lasers, the detectors). As students discussed their plans and built the models, they were seen mimicking components of the model. We noticed that most students were unable to recollect the names of the AFM parts during both the pilot and revised module. Rather they used body language, gestures and descriptions to denote parts. In this case, where the vocabulary was new, gestures and body language were seen as a productive resource (Flood, et al., 2014) in building understanding of the new concepts. We did not insist that students come up with the correct words. Rather, we used their descriptions to probe their understanding of the AFM parts and then provided with corresponding vocabulary, promoting concept development first and then vocabulary building. The modeling task seemed to complement this approach since it allowed students to create their models based on their understanding, which in turn prioritized concept development. We observed that one group in particular, was trying to stabilize the column that would hold the cantilever. They debated over the distance and angle
between the cantilever and the detectors (two AFM sub-systems). In doing so, they considered how the position of the reflective surface matters in the laser/reflectorsub-system. They focused on various sub-systems at a time, their inter-dependence and how they work together to produce the image. The hands-on experience that was structured as a group task created space for them to study the subsystems and tease out elements that contribute to the final image production. This experience also allowed students to collaborate with their peers, which is a cornerstone of constructionist learning experiences (Harel and Papert, 1991). A good understanding of the tool itself can enable the user to use the technology in better and effective ways to analyze data. We see the ability of our modules to help better understand and hence better utilize the technology.

Post the modeling task, students presented their models and explained how their sub-systems of the model work to image a sample. Once again, we noticed that not all groups could use the correct vocabulary to name each system. Yet, they clearly described the role of the part and its position. It suggests that the LEGO model was perhaps useful in visualizing the AFM for students to be able to recreate it accurately. We also noticed that some students took the modeling task one step further and not only made their prototypes able to physically move, but also asked to test their prototype using a laser pointer and reflective surface to see if it would work like the LEGO AFM. Others incorporated cantilevers that would move up and down when scanning a surface, like the LEGO model. There are strong implications for the nature of modeling task introduced in the class. Although the task called for students to create non-functional prototypes, the modeling task was not superficial. It helped students build and demonstrate understanding of the LEGO AFM model. As students get older, they tend to have fewer hands-on experiences with those being limited to cook-book style lab experiments. However, the freedom to play and manipulate materials in an open-structured way allowed students to creatively supplement their knowledge building and hence contribute to learning the new
concept. The accessibility of the materials such as clay and popsicle sticks can make a novel concept like nanotechnology seem less daunting allowing students to explore it at their own pace. We hence find that a) multiple experiences in different formats allow students to make sense of the content in a variety of ways, b) the LEGO AFM helped students visualize what might be happening inside a true AFM, and c) giving students the liberty to play with materials is a key module component.

5.2 Discussion

5.2.1 Student Engagement and Evolution of Student Ideas

During the introductory lesson students were given a survey asking what they liked most about the lesson. The survey demonstrated excitement towards the LEGO AFM. This, along with agreement from the teachers, ensured we would keep the LEGO AFM as a focus moving forward. Following the introductory session, the pilot module included opportunities for students to reflect on the LEGO AFM, and the real AFM. When asked about how the imaging process of the LEGO AFM works, students were able to name individual subsystems or components of the AFM but tended to not connect to the imaging process or the subsystems working together as a whole. After the second part of the pilot module, in which students observed real AFM images of the polymer behind a clear plastic cup, students were asked if the AFM images were helpful in understanding the differences between the two cup materials. Most students simply rephrased the question in some way. Some students could describe what they saw in the images but typically did not connect their observations to the investigation question or how the image was created. However, a few students responded with not only a description of the image, but were also able to connect back to its properties to answer why one cup was more flexible than the other. Responses such as these suggested that with enough scaf-
folds and time when breaking down the tool, students may better understand its abilities and applications. This observation influenced the major revisions to the pilot module, giving students the chance to spend more time with the AFM during the revised module, engaging in multiple experiences to solidify the concepts. During the pilot module, students also answered questions about potential problems with the LEGO AFM. Students were able to identify possible points of inaccuracy, mainly pointing to the size and bulkiness of LEGOs or inaccuracy with the laser subsystem. Students also responded to a question asking about changes to be made to the LEGO AFM to make it functional for smaller samples. Most responses focused on the cantilever tip and making it smaller. Neither set of responses elaborated on their statements, nor connected back to the imaging process. Vague responses from the students supported the need for extra time with the AFM to better understand the entire system as a whole. Nonetheless, it was clear students were thinking about the functionality of the technology, which was a goal of the technology-based approach. Our results directly fed into the revisions of the pilot module, emphasizing the importance of developing a strong conceptual understanding of the tool as a pre-requisite to understanding its applications. Thus, the revised module focused solely on the LEGO AFM, as described in the previous chapter.

Responses to the open-ended question of the content questionnaire from the revised module were analyzed for recurring themes both before and after the module. The pre-module responses showed that the majority of students responded along the lines of “I don’t know.” However, post-module, the majority of responses mentioned size or scale, a key idea of NST (Stevens, et al., 2009). Though our focus was not explicitly on any particular key idea of NST, students appear to have grasped the concept of size and scale after participating in the revised module. Other post module responses further included specific examples to highlight the importance of NST (such as AFM). Responses like these suggest that a number of students had enough support during the
revised module to identify the function and applications of the AFM. This was a significant observation, because expanding the time spent exploring the LEGO AFM to better understand the working of the tool was an intentional revision to the pilot module. Some post-module responses built upon their original ideas from the pre-module questionnaires. Responses such as these echo the structure of the module; students built upon their ideas of NST after engaging with a technological tool, which was the intention behind a constructionist-inspired, application-based module. The multiple-choice questions showed a positive change in number of accurate answers when comparing the pre- and post- answers, though no statistically significant change was found.

Exit tickets given to students asked about the usefulness of the LEGO model. We noticed how students were appreciating the LEGO AFM’s accessibility, one response saying it was “kid friendly.” In other responses, students elaborated on specific subsystems, named particular components, and generally demonstrated understanding of the physical model. Student responses suggest to us the potential engagement and interest the tool has created for the students. The student responses also suggest the LEGO model was helpful to students in understanding the AFM. Classroom videos captured the students working together to build and present their own AFM models. First, they were seen building their AFM models. The videos showed that the use of familiar materials during the modeling activity made it easier for students to have conversations about the tool without explicit scientific vocabulary. It was clear that they were drawing from having seen the LEGO AFM shortly before. The videos showed students in one group discussing the distance between the cantilever and laser beam detector. This moment captured this group of students thinking about the nuances of the build, and what might be required of it, if it were to work. Finally, when the students were asked to present their models at the end of class, the videos showed use of body language and gesture to describe elements of the AFM. However, all groups were able to present their model
and explain each components’ function, even if they were lacking the specific vocabulary. This tells us that the modeling approach possibly allowed students to explore the AFM through modeling with familiar materials may have been useful in building their understanding of the tool.

Student ideas about the AFM have evolved as a result of using MER to develop NST modules for grade 8. During the introductory lesson, students were shown the LEGO AFM without much context, but expressed interest in the model. The pilot module presented students with a lot of information, but in a short amount of time. Student responses from the pilot module echo this, showing that students picked apart individual components of the AFM, but did not connect back to the system as a whole. However, after two rounds of editing attending to student conceptions about the AFM, the revised module resulted in deeper understanding of the tool, its components, and how it works to produce an image. Students were able to build models and describe the models’ subsystems and the way the subsystems work synchronously, even if they did not have the technical language to do so. From this evolution, it is clear that revising a learning experience with consideration of conceptions students already have creates a more meaningful environment for students to explore extremely new scientific content that would otherwise be inaccessible to them.

5.2.2 Teacher Preparedness

MER includes the teacher perspective during the recursive process, asking teachers to evaluate their own content knowledge (Component A), and account for the student audience (Component B). Throughout the study, teachers’ inputs have been valued towards evaluating and designing the modules. Although the research team presented scientifically coherent content knowledge about the AFM and NST, we needed inputs on best ways to introduce the novel content to grade 8 and 9. The participating expert teach-
ers shared the relevant standards, practices, and best facilitation techniques. They also shared ideas about points in their curriculum where the pre-existing content could be connected to NST, such as the connection to polymers in high school chemistry. These inputs helped create an effective learning environment suitable for our target audience of grade 8 and 9. Our main collaborating teacher worked with us for a period of two years, during which she was involved in the process of looking into relevant standards, suggesting activities for the pilot module, observing the pilot module as a learner, and evaluating the pilot module from that perspective. During the teacher’s engagement with the cyclical MER process, she had the opportunity to continually observe the classroom from an outside perspective first, having seen initial facilitation of the content by the researchers during the pilot module. She also had the opportunity to unpack the relevant content herself first, as a learner of NST. After engaging with the module from a students’ perspective, and participating in the revision process, the teacher was then able to comfortably facilitate the revised module.

One aspect of MER that I found important was its attention to building on teachers’ pedagogical content knowledge (PCK) (Duit, et al., 2012). PCK links understanding of the content with teaching practices (Shulman, 1987). Shulman considers PCK to be a critical part of successful teaching. Thoroughly formed PCK of a topic can help teachers plan how they will organize and present information or adjust it as needed to attend to different needs of the students (Van Dijk Kattmann, 2007). Using MER to develop lessons can potentially improve teachers’ PCK as it gives them a chance to evaluate their lesson plans and facilitation strategies for specific disciplinary learning. During the iterative process, we interviewed the teacher after she facilitated the revised module. We discussed the appropriateness of the content, the alignment of the activities and the materials in facilitating the content, and the level of her preparedness to facilitate. In the interview (Appendix C), the teacher shared that she felt prepared to teach the revised
module after the pilot module had been updated, due to becoming familiar with the content and module over time. This evolution may suggest that the teacher developed both her content knowledge about NST, while considering how to best present the novel content to her students.

Ultimately, her engagement in this process allowed her to critically evaluate the modules. Her participation provided her with opportunities that could have deepened her content knowledge about NST to where she could have felt confident to teach the module on her own. While her content knowledge may have been further developed, through participating in the iterative process, it is possible she developed ideas towards her pedagogical knowledge about NST, towards her PCK of NST. While we cannot entirely generalize results based on this particular case, our results do suggest that MER has opportunities for teachers, not just to strengthen their own ideas surrounding novel concepts, but also has the ability to contribute to their pedagogical content knowledge about a topic. Based on the results, we also see the value in using MER as a method of improving teacher PCK to further benefit students in the learning environment.
CHAPTER 6

CONCLUSIONS

6.1 Conclusions

This study included three rounds of developing, implementing, evaluating, and revising an NST module for grade 8 using MER as a framework. The first round included discussions with teachers and a short presentation with students from grades 8 to 10 to collect initial data and feedback towards planning a module. Feedback from teachers pointed to connections with the relevant standards, support of a technology-based approach, and a connection to polymer labs in chemistry. The students showed positive interest in the LEGO AFM in responses to a post-presentation survey. The second round included the implementation of the pilot module with a different collaborating teacher and a new set of grade 8 students, in which students were introduced to the LEGO AFM, completed a modeling activity, and reflected on the LEGO AFM’s usefulness as a model. This was followed by use of a real AFM to examine two different kinds of polymers. Evaluation of the pilot module showed students beginning to understand the tools’ individual subsystems but not their collective functions. S-STEM Survey results showed positive changes from pre- to post-module in attitudes towards a handful of STEM careers and subjects. This result informed revisions for the third and final round. The revised module, in turn, included more time breaking down the subsystems that make up an AFM, and the modeling activity. By this point in the cycle, the teacher was able to lead the
module. The revised module resulted in students having a clearer understanding of each of the individual components of the AFM, and enhanced understanding of the AFM’s functionality and the key NST concept of size and scale. The revised module also resulted in positive change from pre- to post-module in attitude in more STEM careers on the S-STEM surveys than the pilot module. An interview with the collaborating teacher was conducted, where she reiterated that she ultimately felt prepared to teach the NST module after participating in and contributing to the MER cycle.

Our results suggest that student ideas about the components and working of an AFM evolved as we cycled through revising the module, conforming to the literature supporting MER as a lesson development tool for novel science content. Giving students more support, as in multiple experiences regarding the same concepts, and more time with the concepts, can lead to better understanding of a system like an AFM. From implementing this revision and observing the evolution of student ideas, the results suggest that active evaluation and revision can create a more meaningful learning experience wherein students to discover new concepts through a technology. Use of technology has shown to be an effective starting point for introducing NST. Though we cannot make any direct claims about the results from the S-STEM surveys due to the short duration of the modules, the results highlight increased attitudes towards STEM subjects and interest in STEM careers between the pilot and revised module. This result indicates the possibility of revisions attending to student ideas being effective in developing positive attitudes towards STEM, and that a well-developed NST module may have positive impact on student attitudes as well. Finally, a discussion with the teacher demonstrated that participation in the cyclic process of MER built both content and pedagogical knowledge about teaching NST for that particular teacher. While this result is not generalizable, it does suggest that participation in MER may enhance teachers’ PCK.
6.2 Limitations

The main limitation I perceive for this study is that the scale of the study does not allow us to generalize our results. The pilot and revised modules were only implemented with one teacher at one school, for short durations. One goal of the study was to investigate changes in students’ attitudes towards STEM via the S-STEM surveys after participating in the modules. Research has shown that when shaping student’s overall beliefs or attitudes towards a discipline, longer periods of exposure can have a deeper influence (Tang, Delgado, and Moje, 2014). However, it can be challenging for teachers to accommodate implementation of a new module within their plans. Research has also suggested that teachers with less experience with a topic like NST may be less comfortable implementing unfamiliar content in their classrooms (Blonder and Sakhnini, 2017). Therefore, our study was limited to these constraints. Because the modules individually ran for short periods of time for each group of students, we cannot make direct claims about the results of the S-STEM surveys. Nevertheless, results from the surveys highlight a positive shift in students’ attitudes as a result of the learning experience.

6.3 Implications

Our results demonstrate the MER’s effectiveness in developing, implementing, evaluating, and revising a learning experience to ultimately create a more meaningful environment for students to discover new ideas that would typically be out of reach for their grade level. Based on our results, we suggest the use of MER to develop NST content for late middle school students and introduce the NST content to teachers. Attending to student ideas when planning a lesson ensures that the facilitation is well suited to the audience (Duit, et al., 2012). Meanwhile, teachers’ participation in the MER pro-
cess can positively impact their combined pedagogical and content knowledge about the subject matter (Kattmann, et al., 1996). Though our study focuses on NST specifically, the MER can be applied more broadly to related scientific disciplines to improve science teaching and learning.

Based on the results pertaining to the structure of the module, we suggest the use of a technological tool to introduce NST concepts as early as grade 8. The technology-based approach created a meaningful environment for students’ contextualized learning. Student responses throughout the modules showed that the LEGO AFM was useful in helping students visualize and understand objects at a scale that is otherwise invisible to them. Along with a focus on application-based approach for exploring newer concepts, we also focused on hands-on learning and attempted to give students thinking spaces, enabling them to discover NST concepts with self- and peer-guided experiences.

A goal of the study was to investigate students’ attitudes towards STEM throughout implementation of the modules. Research has shown that study of nanoscale properties using technology can spark students’ excitement about STEM fields (Greenberg, 2009). As the module was revised, the S-STEM surveys showed even higher positive change in the pre- and post-module results between the pilot and revised module. Use of MER may be helpful in shaping students’ attitudes and beliefs towards STEM subjects and careers. At the same time, application-based experiences can help students seamlessly translate content learned in school to industry (Roco and Bainbridge, 2005). Therefore, an NST module like ours could have the potential to contribute to the next generation of the STEM workforce.
6.4 Reflections

As a student of physics, a core discipline that is closely related to NST, participating in the study has given me a new perspective on teaching topics with underlying physics concepts. Both working within the MER framework, and developing a technology-based learning experience to introduce new concepts have been valuable to me as a learner and educator. In this section, I will share some reflections on this experience, after having worked on this study since I began my program, almost two years ago.

One of the key aspects of the MER framework is the consideration of students’ pre-existing conceptions about a topic when creating a learning experience for them, regardless of how they are reasoned or articulated. I entered my undergraduate studies in physics coming from a performing arts high school, where options for math and science classes were scarce. Because of this, I often struggled during physics classes that were lecture-heavy and entirely abstract, not having thoroughly developed fundamental pre-calculus and calculus concepts. Having limited exposure to physics and the related math was my context as a student entering undergraduate physics classes, a background that my professors might not have considered. Though this study has been with grade 8 students and I am reflecting on my college experience, I found myself noticing the value of this component of MER. It is logical that a learning experience may be more meaningful to more students if a variety of backgrounds are considered during planning. I also found multiple kinds of experiences or teaching angles to be useful when trying to understand how a system of any kind (abstract or tangible) works. I wondered why I had not typically seen this kind of approach in my physics classes; after all, understanding a system is often the goal in physics.

Having seen the benefit of breaking down a machine to its barest components and functions before using it, I wish I had more experience in instrumentation and modern
technology throughout not just my undergraduate career, but in K-12 as well. The AFM is a tool that physicists use today (Pooser, et al., 2020), and I had no prior exposure to it myself. Personally, it is possible that exposure to the AFM or any other modern industry tool would have had a positive effect on me as a student having to consider college and career choices. The meaningful experiences throughout my high school physics, math, and astronomy classes led me to an interest in an astrophysics major in college, so it would not be unexpected for me to have enjoyed an NST module like ours. However, I am just one student with lifelong general interest towards STEM subjects. Still, after this experience, I hope access to NST industry tools continues to expand for students in all grades. Anecdotally, I have seen that modern technologies appeal to students in grades 7-12 and based on participating in this study and my personal experience, I believe students would likely benefit from working with industry tools before they go on to make college and career choices.

Currently, my only experience teaching is having taught introductory undergraduate physics classes both in a university setting and a test preparation setting. Otherwise, participating in this study has been the first time I have worked with K-12 students. During this experience, I have introduced myself to educational theory I had not seen before, including constructivism/constructionism, MER, and the 5E model. Though I have had a brief introduction to learning theories in a previous educational psychology course, I had much to learn about these frameworks for learning and teaching before contributing to module planning. However, I have come out of this experience with some newfound training in science teaching, that I would not otherwise have received studying physics alone.
APPENDIX A

S-STEM SURVEYS

SURVEY

DIRECTIONS:

There are lists of statements on the following pages. Please mark your answer sheets by marking how you feel about each statement. For example:

<table>
<thead>
<tr>
<th>Example 1: I like ice-cream.</th>
<th>Strongly Disagree</th>
<th>Disagree</th>
<th>Neither Agree nor Disagree</th>
<th>Agree</th>
<th>Strongly Agree</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
</tbody>
</table>

As you read the sentence, you will know whether you agree or disagree. Fill in the circle that describes how much you agree or disagree.

Even though some statements are very similar, please answer each statement. This is not timed; work fast, but carefully.

There are no "right" or "wrong" answers! The only correct responses are those that are true for you. Whenever possible, let the things that have happened to you help you make a choice.

PLEASE FILL IN ONLY ONE ANSWER PER QUESTION.
### Math

<table>
<thead>
<tr>
<th></th>
<th>Strongly Disagree</th>
<th>Disagree</th>
<th>Neither Agree nor Disagree</th>
<th>Agree</th>
<th>Strongly Agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Math has been my worst subject.</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>2. I would consider choosing a career that uses math.</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>3. Math is hard for me.</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>4. I am the type of student to do well in math.</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>5. I can handle most subjects well, but I cannot do a good job with math.</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>6. I can get good grades in math.</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>7. I am good at math.</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
</tbody>
</table>

### Science

<table>
<thead>
<tr>
<th></th>
<th>Strongly Disagree</th>
<th>Disagree</th>
<th>Neither Agree nor Disagree</th>
<th>Agree</th>
<th>Strongly Agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>8. I would consider a career in science.</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>9. Knowing science will help me earn a living.</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>10. Science will be important to me in my life’s work.</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>11. I can handle most subjects well, but I cannot do a good job with science.</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>12. I am sure I could do advanced work in science.</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
</tbody>
</table>
**Engineering and Technology**

Please read this paragraph before you answer the questions.

Engineers use math, science, and creativity to research and solve problems that improve everyone’s life and to invent new products. There are many different types of engineering, such as chemical, electrical, computer, mechanical, civil, environmental, and biomedical. Engineers design and improve things like bridges, cars, fabrics, foods, and virtual reality amusement parks. Technologists implement the designs that engineers develop; they build, test, and maintain products and processes.

<table>
<thead>
<tr>
<th></th>
<th>Strongly Disagree</th>
<th>Disagree</th>
<th>Neither Agree nor Disagree</th>
<th>Agree</th>
<th>Strongly Agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>13. I like to imagine creating new products.</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
</tr>
<tr>
<td>14. If I learn engineering, then I can improve things that people use every day.</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
</tr>
<tr>
<td>15. I am good at building and fixing things.</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
</tr>
<tr>
<td>16. I am interested in what makes machines work.</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
</tr>
<tr>
<td>17. Designing products or structures will be important for my future work.</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
</tr>
<tr>
<td>18. I am curious about how electronics work.</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
</tr>
<tr>
<td>19. I would like to use creativity and innovation in my future work.</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
</tr>
<tr>
<td>20. Knowing how to use math and science together will allow me to invent useful things.</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
</tr>
<tr>
<td>21. I believe I can pursue a career in engineering.</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
</tr>
</tbody>
</table>
Your Future

Here are descriptions of subject areas that involve math, science, engineering and/or technology, and lists of jobs connected to each subject area. As you read the list below, you will know how interested you are in the subject and the jobs. Fill in the circle that relates to how interested you are.

There are no “right” or “wrong” answers. The only correct responses are those that are true for you.

<table>
<thead>
<tr>
<th>Subject Area</th>
<th>Not at all Interested</th>
<th>Not So Interested</th>
<th>Interested</th>
<th>Very Interested</th>
<th>I don’t understand this</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. <strong>Physics</strong>: include studying the nature of the universe. <em>(physicist, astronomer)</em></td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>2. <strong>Environmental Work</strong>: understanding physical and biological processes that govern the environment. This includes finding and designing solutions to problems like pollution, reusing waste and recycling.</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>3. <strong>Biology and Zoology</strong>: involve the study of living organisms and the processes of life.</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>4. <strong>Veterinary Work</strong>: involves the science of preventing or treating disease in animals.</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>5. <strong>Mathematics</strong></td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>6. <strong>Medicine:</strong> (E.g. physician’s assistant, nurse, doctor, nutritionist, emergency medical technician, physical therapist, dentist)</td>
<td>Not at all Interested</td>
<td>Not So Interested</td>
<td>Interested</td>
<td>Very Interested</td>
<td>I don’t understand this</td>
</tr>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>7. <strong>Earth Science:</strong> is the study of earth, including the air, land, and ocean.</th>
<th>Not at all Interested</th>
<th>Not So Interested</th>
<th>Interested</th>
<th>Very Interested</th>
<th>I don’t understand this</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>8. <strong>Computer Science</strong></th>
<th>Not at all Interested</th>
<th>Not So Interested</th>
<th>Interested</th>
<th>Very Interested</th>
<th>I don’t understand this</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>9. <strong>Medical Science:</strong> involves researching human disease and working to find new solutions to human health problems. (medical scientist, pharmacologist)</th>
<th>Not at all Interested</th>
<th>Not So Interested</th>
<th>Interested</th>
<th>Very Interested</th>
<th>I don’t understand this</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>10. <strong>Chemistry</strong></th>
<th>Not at all Interested</th>
<th>Not So Interested</th>
<th>Interested</th>
<th>Very Interested</th>
<th>I don’t understand this</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>11. <strong>Engineering</strong></th>
<th>Not at all Interested</th>
<th>Not So Interested</th>
<th>Interested</th>
<th>Very Interested</th>
<th>I don’t understand this</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
</tbody>
</table>
About Yourself

DIRECTIONS: In the following series of questions, you will skip certain questions based on how you answered previous questions.

1. Do you plan to go to college?
   - Yes
   - No
   - Not Sure

2. In the future, do you plan to take advanced classes in:

<table>
<thead>
<tr>
<th></th>
<th>Yes</th>
<th>No</th>
<th>Not Sure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mathematics?</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Science?</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
</tbody>
</table>

3. More about you.

<table>
<thead>
<tr>
<th></th>
<th>Yes</th>
<th>No</th>
<th>Not Sure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Do you know any adults who work as scientists?</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Do you know any adults who work as engineers?</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Do you know any adults who work as mathematicians?</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Do you know any adults who work as technologists?</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
</tbody>
</table>
CONTENT QUESTIONS

1. The field of Nanotechnology involves
   A: Structures, devices, or systems having novel properties due to the arrangement of structures on the 1 to 100 nm scale.
   B: Structures, devices, or systems having novel properties due to the arrangement of structures on the 1 to 10 nm scale.
   C: Structures, devices, or systems having novel properties due to the arrangement of structures on the 1 nm to 1 m scale.

2. What piece of equipment is best used to create an image of an object with a critical dimension of 10 nm?
   A. Electron microscope
   B. Optical microscope
   C. Magnifying glass
   D. Pair of glasses

3. One nanometer is a __________ of a meter
   A. Millionth
   B. Billionth
   C. $10^{-9}$
   D. None

4. Have you heard of the term Photolithography? What does that mean?

5. Can you suggest why shorter wavelength light is used to expose patterns in photolithography over longer wavelength light?

6. Why do you think Nanotechnology in today’s world is important? And does the use of this technology impact the environment?
APPENDIX C

TEACHER INTERVIEW QUESTIONS

Profile questions:
1. How long have you been teaching?
2. How long have you been teaching at this school?
3. How would you describe the demographic background of your school?

Logistical questions:
1. Do you feel that the module, including the teacher background information document had all the materials and information you needed to prepare for teaching it?
2. Every teacher adjusts lesson plans for their classes, techniques, etc. and that’s expected. I’d like to know your reasons behind changes you made in the latest module as it relates to this particular group of students.
3. Are there any other changes you might suggest moving forward? I know we ended up introducing a lot more hands on experiences and found that to be useful.

Student engagement based questions:
Before beginning these questions, I shared the results so far with the collaborating teacher.
1. Did you notice any changes between the first and second round in how engaged the students were during the lesson?

2. Did you notice any changes between the first and second round in interest of the subject as a whole?

3. Based on your experiences, do you think there’s a place for nanoscience and technology concepts in high school?
APPENDIX D

STUDENT REFLECTION QUESTIONS

**Pilot module:**
During class, students were asked to discuss and record answers to content probing questions in groups of four:

1. How does the AFM image the surface?
2. To image something very small, how should the LEGO AFM be changed?
3. What are some problems with the LEGO model?

At the end of the module, students individually responded to the question, “Did the AFM help you understand the differences in the physical properties of the two cups? How?”

**Revised module:**
Post-module reflection questions:

1. In what ways was the LEGO AFM model helpful in understanding how an AFM works?
2. Reflect on the usefulness of the AFM. What is the purpose of an AFM?
3. If we want to image something even smaller, something at the actual nanoscale, how do we change the LEGO AFM?


Friday Institute for Educational Innovation (2012). Student Attitudes toward STEM Survey- Middle and High School Students, Raleigh, NC


