ABSTRACT

BEDWARD, JOHN CURTIN. Exploring Elementary Students’ Use of Semiotic Tools and Self-Explanations when Learning about the Particulate Nature of Matter. (Under the direction of committee Eric N. Wiebe).

Elementary science continues to undergo school-based reform initiatives. Elementary model-based inquiry (MBI)—student constructed models, kit-based science, collaboration, discourse, and instructional scaffolds—offer a way forward in supporting abstract thinking. A possible bridge between student perception-bound thinking and symbolic thinking is the particulate nature of matter (PNM). This “big idea” in science helps explain a host of physical science phenomena observed in nature or through experimentation. Along with MBI, PNM can promote scientific reasoning during the early years of student growth. A mixed methods multi-case semiotic approach was used to engage Grade 3 (N=22) & 5 (N=30) students in Soils and Landforms curriculum, respectively. A Science Learning Trajectory Assessment Instrument was developed to assess student explanations across four modalities—graphical, textual, verbal and gestural. The triangulation of student classroom experience, their notebooks and video taped interviews were used to analyze student work. For Grade 3 students descriptive statistics revealed distinct patterns in student model-based discourse and sign use across the four modalities. Sixty-six percent of students’ demonstrated improvement on their pre-posttest while 54 percent demonstrated no improvement. Scores pertaining to soil and water interactions showed slight improvement in their graphical-textual and verbal-gestural responses. Students incorporated a variety of sign types (iconic, indexical and symbolic) across all modalities and more often used symbolic signs to represent an iconic view of the phenomena. An emergent finding was the use of gestures (indexical + iconic) signs to represent macroscopic views of soil. The scores
revealed patterns that could not be fully explained quantitatively. Within-case analysis representing (N=11) was used to describe and explain their verbal responses. Two students showed promise incorporating abstract science conceptions with their macroscopic observations. As a result of the individual cases, cross case synthesis of student metamodeling and graphic editing was generated. The majority of students leveraged the modeling tools to clarify, emphasize or “add to” their existing explanation. Students’ graphical representations remained at a macroparticulate level. The incorporation of semiotics provided an opportunity to analyze sign use in a more integrative manner.
Exploring Elementary Students’ Use of Semiotic Tools and Self-Explanations when Learning about the Particulate Nature of Matter

by
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DEDICATION

I dedicate this dissertation to Lisa M. Marshall for her unconditional support and encouragement throughout every stage of the process.
BIOGRAPHY

John Bedward was born and raised in Ottawa, Canada. He is the son of Nessa Sherwood and Ven Bedward, and one of five siblings. His formative years were spent in French Roman Catholic school system. His professional career includes 10 years coaching and managing recreational facilities, and eleven years in pre-press production, information design and publishing. During this period he was involved in community radio, mixed media productions, and co-owner of a local bookstore. John moved to the United States in 1999 to further his career as a product manager in distributed computing applications and pursue studies in science and technology education. John is married to Lisa M. Marshall.
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CHAPTER ONE

INTRODUCTION

Over the past 15 years several reform based education documents have influenced the direction of elementary science instruction. The *Benchmarks for Science Literacy*, the *National Science Education Standards* and *Taking Science to School* promote learning by inquiry, suggest anchoring science concepts, process skills and nature of science around “big ideas” in science, and encourage pedagogical practices that place the student at the center of the learning experience (AAAS, 1993; NRC, 1996; NRC, 2007). More recently, *A K-12 Framework for Science Education* put forth the need to align curriculum that leverages science, technology and engineering more explicitly (NRC, 2011). These documents echo a national discourse emphasizing the need for a healthy STEM citizenry and STEM workforce to support goals of global competitiveness and economic growth (PCAST, 2010). This national discussion is in conjunction with current pedagogical practices and assessments that embrace 21st century science and technology skills—creativity, critical thinking and problem solving—which have been found to affect student cognitive, affective and socio-cultural domains of learning (Kinshuk, Ifenthaler, Spector, Sampson, & Isias, 2010; Pellegrino & Quellmalz, 2010; P21, 2011). McKay & McGrath (2007) suggest the need to embrace student innate intellectual curiosity, creativity and personal interests in order to balance social demands with individual aspirations. Measurement of these goals remains a challenge. An ongoing conversation of student assessment that reflects the push for authentic inquiry science practices (e.g., scientific thinking and discourse), socioprofessional practices (e.g., representational systems and science journaling) and experiences that support student academic performance on local, national and international assessments are important aspects
of educational reform (Jaipal, 2009; Louca, Zacharia & Constantinou, 2011; NAEP, 2011; Ruiz-Primo, Min, Ayala & Shavelson, 2010). These national goals can be accomplished by providing opportunities to help students leverage their prior experience and encourage deep and sustained exploration of science subject matter (NRC, 2007). According to the National Research Council bridging the inquiry process, representational practices, and student interaction and discourse may better prepare students for middle and high school STEM curriculum.

**The Elementary Grades**

A good place to begin students’ engagement with critical thinking exercises is in the upper elementary grades, where national policy aspirations come face-to-face with current science instructional practices as currently implemented (NCES, 2011). The science classroom curriculum remains crowded and often includes many aspects of technological and engineering literacy goals (ITEA, 2000; NAE, 2010). Curriculum packages such as *Seeds of Science/Roots of Reading* (The Lawrence Hall of Science (LHS), 2011) assist by combining literacy and scientific inquiry. The *Engineering is Elementary* (Museum of Science, 2011) curriculum emphasizes an engineering design, inquiry and problem solving, and current kit-based science (FOSSweb, 2008) curriculum promotes a guided inquiry framework.

These are all viable ways of introducing students to science. However, there remains a challenge of how to help students link their observations to many of the abstract science concepts discussed in these varied curricular approaches. Teachers lack the pedagogical resources, tools, time and often the background knowledge to support students in abstract thinking around science concepts that are difficult to experience (NRC, 2007). For instance,
abstract ideas (e.g., gravity, friction & force) greatly influence a students’ understanding of the relationship between soil saturation, erosion or deposition. More research is needed in developing elementary science resources to support teachers and students in this endeavor (Wiebe, Madden, Bedward, Minogue & Carter, 2009).

More specifically, Grade 3 Soils and Grade 5 Landforms curriculum from the FOSSweb kits provide a chance for students to explore many aspects of physical science phenomenon that remain difficult terrain for students to master. Many of these concepts require students to make sense of phenomena by combining observable characteristics of soil properties and underlying invisible, microscopic processes of erosion and deposition (FOSSweb, 2008; STC, 2010). These two kits provide a good example of how many scientific concepts and ways of thinking students are expected to master, to some degree.

For instance, in Grades 3 Soils, students must be able to observe and describe the properties of soil; observe how different soils absorb water at different rates; determine the ability of soil to support plant growth; understand the role of composting in soil formation; and recognize air as a substance that takes up space and has mass (NCDPI, 2004). In Grades 5 Landforms, students must be able to identify and analyze forces that cause change in landforms over time; investigate the role of the water cycle and how the movement of water shapes landscapes; discuss the role of erosion in forming new landforms (canyons, valleys, meanders, and tributaries); describe the deposition of eroded material and its importance in landform creation (e.g., deltas and flood plains); identify and use models, maps and aerial photographs to represent landforms; discuss how humans influence erosion and deposition in local settings; and be able to explain how gravity, friction and change in mass affect the
motion of objects (NCDPI, 2004/2008; NRC, 1996 p. 134; NCES, 2011; AAAS, 1993; Gonzales, Williams, Joycelyn, Roey, Kastberg, & Brenwald, 2009). By the time students leave the elementary grades they should have experienced the role of models in revising and explaining phenomena, be able to associate aspects of form and function to explain the behavior of material and phenomena, and participate in science inquiry and technological problem solving activities that encourage the use of multiple process skills, both cognitive and procedural (NRC, 1996; NRC, 2007; ITEA, 2000; NAE, 2010).

**Elementary Science Proficiency Performance**

Although the aspirations for learning science are high, there are several indicators that suggest students in later elementary grades are not performing as well as expected. On the *Trends in International Mathematics and Science Study (TIMSS)*, 2007 scores focused on elementary physical science content and cognitive domains (e.g., knowing, applying and reasoning skills), were virtually unchanged since 1995. In fact, only 15% of U.S. fourth graders scored at or above the international benchmark in science. As well, the findings indicate that test scores on TIMSS continue to decrease as school age children continue to matriculate (PCAST, 2010; Gonzales et al., 2009). Further evidence suggests the majority of students (72%) perform at or slightly above basic level (e.g., knowing the properties of the states of matter), while a very small percentage (1%) perform at an advanced level (e.g., *fluency in the use of representations and designing investigations*). The remaining third of students tested (34%) performed at or above proficiency level (e.g., ability to design and carry out an investigation). More research is needed to address the large number of students who are scoring at basic science proficiency or lower against the national aspirational
goals—critical thinking, collaborative practice and constructing evidence-based scientific explanations. We assert research that examines inquiry science, science content, student curiosity and science standards in authentic settings will give us insights on advancing students’ scientific reasoning.

**Foundational Images**

The DRK-12 NSF funded Graphically-enhanced Elementary Science project was designed to explore student-generated graphical representations in Grades 2-5 elementary science (Wiebe, Minogue, Carter, Bedward & Madden, 2010). Wiebe, Carter, Minogue, Madden & Bedward (submitted) found that more scaffolding of student representational practice throughout the inquiry-based science teaching and learning cycle was needed to support student thinking. Specifically, the project suggests the need to further student thinking that connects visible observations to invisible aspects of a phenomenon. For example, students investigating erosion and deposition spent a lot of time creating representations depicting their stream table set up and initial observations, but few students represented the processes or influences (e.g., gravity and slope) that affected rate of erosion. With the introduction of graphic tools teachers were able to bridge student initial observations with underlying science processes. This work resulted in an online teacher professional development site of best practices that encourages deeper integration of graphics, pedagogy and science content (http://gess.fi.ncsu.edu). A central feature of teacher professional development materials was the introduction of foundational images (i.e., graphic tools and scale tools) that support student thinking on the objects, processes and interactions that help to explain natural phenomena. For instance, introducing vectors, as a symbolic tool
illustrating a force, along with student observational drawings to reveal invisible forces (e.g., gravity) that influence landform creation (http://gess.fi.ncsu.edu). A particle tool can be used to describe how different soil properties of sand versus clay behave differently in water (http://gess.fi.ncsu.edu). Students need opportunities to bridge their classroom experience with science content, which is often invisible, in order to make sense of phenomena (Wiebe, et al., 2010). As well as opportunities to reflect on their science ideas and critically assess their observations in order to develop reasonable explanations. One promising support for student thinking throughout the inquiry process is a graphic-enhanced science notebook.

**Science Notebooks**

Much of elementary science learning centers on kit-based science curricula, where inquiry and technological problem solving are combined to promote science process skills (e.g., observation and measurement) science content (e.g., erosion and deposition) and nature of science skills (e.g., the social and empirical dimensions of science) (FOSSweb, 2008; LHS, 2011). The science kits provide students, opportunities to generate graphic representations, promote guided inquiry-based science, and encourage the use of science notebooks as a repository of student work (FOSSweb, 2008; STC, 2010). The science notebook is an ideal medium for students to explore inscriptive practices, support student reflection, and encourage sense making (Ruiz-Primo et al., 2004). Finally, science notebooks can potentially provide a means for students and teachers to engage in discourse through the use of teacher formative assessment practice wherein student work can inform teachers of students’ future learning needs (Wiebe, Madden, Bedward, Minogue & Carter, 2008; Wiebe et al., 2009). However, Wiebe et al., 2010 conducted an extensive examination of
photographic documentation of student notebook use, and found that student written explanation and graphic representations often emphasize surface level understanding of phenomena (e.g., concrete observations). The researchers determined that students in the study were lacking opportunities to connect macroscopic observations and invisible or near invisible processes and interactions that might better explain a phenomenon (e.g., the influence of gravity or particle size on erosion).

**Model-based Inquiry**

Model-based inquiry may provide a bridge to support student representational practice, encouraging deeper scientific thinking. Previous research suggests that students engaged in model-based inquiry activities further their understanding of natural phenomena (Abdo & Taber, 2009; Bailer-Jones, 2003; Clement, 2000). Findings indicate that it is especially important to engage students in constructing more robust conceptual understanding of science involving observable phenomenon and invisible science ideas.

Modeling encourages habits that are practiced throughout many disciplines and professional practice. Experts across the sciences and engineering are dependent on models to construct representations of our known world. The construction of mental models—a cognitive representation of the essential parts of a system or phenomenon—is a necessary function in both research and communication of the empirical world (Bailer-Jones, 2003; Coll, 2005; Massironi, 2002; Mayer, 1998; Windschitl, Thompson & Braaten, 2008). This is because two-dimensional graphic based models or three-dimensional physical models may provide an operational description of how the object, event or phenomenon behaves (Louca et al., 2011). In order for students to engage in aspects of natural phenomenon a variety of resources may
be needed including physical experiments and multimedia content (e.g., animations, video and simulations). For instance Mayer (1998) conducted extensive research on the benefits and use of external representations to promote meaningful student learning. How these static or dynamic representations are organized, how the information is revealed to the reader, and which senses are engaged all have a profound effect on student sense making of science ideas. In the case of the GEES project (Wiebe et al., 2009), the team integrated developmentally appropriate foundational images (i.e. graphic tools and scale tools) along with science inquiry to help students’ reason about abstract concepts. Too often, the process of science becomes the end game of a child’s experience when in fact students should be engaged in building theories and models, and checking them for internal consistency and coherence (NRC, 2007) through testing and experimentation. Recommendations by the National Research Council describe innovative instructional pedagogy that provides students with opportunities to revisit their mental models through the practice of multiple representations. Promising work by Wiebe et al. (2009) and (Louca et al., 2011; Neilson, Campbell & Allred, 2010; Schwarz, Reiser, Davis, Kenyon, Acher, Fortus, Shwartz & Krajcik, 2009) indicate real potential for a model-based approach, using student-generated graphics, to further classroom innovations. But their remains too few studies that connect student generated models and discourse as a means of promoting sense making (Louca et al., 2011).

**Drawing to Learn**

The use of modeling tools, a modeling heuristic used in conjunction with current research in students’ graphical representations, and “drawing to learn” may provide further
insight into how best to support student reasoning in the physical sciences (Ainsworth, Nathan & Van Meter, 2010). Student-generated drawings may encourage their sense making of the world by assisting in the formation of ideas. Drawing can function as a mediator between students’ spontaneous and scientific conceptions, and bridge the gap between perception-bound thinking and more abstract symbolic thinking (Brooks, 2009/2009a). Research by Edens & Potter (2003), Gobert & Clement (1999), Van Meter, Zecevic, Schwartz & Garner (2000), and Van Meter (2001) suggest that student generated drawings support elementary students conceptual understanding of science concepts. Student drawings and words provide another way for them to represent and encode information. According to this research drawings can help students select, organize and integrate words and images into a coherent mental model and serve as analogical models (i.e., a representation) to the phenomenon under investigation. These drawings can also be used as the basis to elicit student self-explanations, which has been shown to further student conceptual understanding (Ainsworth & Loizu 2003).

The pedagogical challenges remain three fold: (1) a lack of effective use of student generated drawings throughout the inquiry process, and (2) teachers lack confidence in scaffolding drawing as a learning tool (Baum, Owen & Oreck, 1997) and (3) it is difficult to support student sense making between their surface level observations with invisible processes that help explain cause and effect. The particulate nature of matter (PNM), a theoretical model of how the natural world is organized, might be a useful way to bridge macroscopic observations and microscopic processes, especially in physical science areas related to Soils and Landforms.
The Particulate Nature of Matter (PNM)

“...matter is composed of particles that are in continuous motion with a vacuum in between them, and electrostatic forces keep the particles together at the solid and liquid state.”
(Adadan, Trundle & Irving 2010, p. 1006)

The Particulate Nature of Matter can be used to support student thinking between observable phenomenon and the influencing microscopic behaviors (Abdo & Taber, 2009). Incorporating this “big idea in science” can help students differentiate between substance, matter and its forms. PNM may provide students with a way to express connections between their visible observations and invisible forces that shape the natural world, and facilitate model and pattern recognition. This may promote generalization and the application of science concepts to a broader range of observable phenomena (Enfield, Smith & Gruber, 2007).

By late elementary school, students are expected to know that matter takes up space and has weight; matter can exists in several forms; matter is conserved; matter is made up of particles that are invisible; and that it is possible to exert a force on an object without touching it (AAAS, 1993; NRC, 1996; Harrison & Tregust, 2002). Model-based inquiry and awareness of modeling (i.e., metamodeling), along with inscriptional practices based on student-generative drawings using science notebooks can be leveraged with PNM to support student sense making. One challenge noted in the literature (Louca et al., 2011) is how to analyze the combined text and graphic entries in science notebooks for evidence of learning through model-based inquiry.
**Semiotics**

In the theory of Semiotics, the study of signs and their meaning, it is suggested that human beings live in a world constructed of signs (e.g., object or phenomenon) who in turn, construct signs to make sense of their world (Deely, 1990). These signs are used in both verbal and non-verbal expression of ideas and as a tool for thinking and reasoning. In essence, the use of signs is a vehicle to interrogate phenomena and provide a systems view of phenomena in relation to its environment and its larger place in nature (Cobley, 2010). Through semiotics, observers can contextualize the discourse (e.g., video tape analysis of classroom interactions), and analyze the types of discourse (e.g., student explanations) across a variety of modes (e.g., verbal, textual, gestural, and or graphical) students use to express their ideas. Students may be unaware they are using a variety of strategies to mediate their understanding of scientific phenomena. These strategies could be physical manipulatives, multimedia, teacher explanations, group discourse, or the phenomenon itself. In short, the use of semiotics can bring into focus a way of understanding student meaning-making during model-based inquiry.

**Research Questions**

A mixed method multiple case study approach will be used to combine a rich description of the science-learning context, student notebook entries, student gestures and verbalizations in an authentic learning environment. The GEES graphic tools (Wiebe et al., 2010) in the context of model-based inquiry will be used to investigate: (1) student-sign generation of their science ideas/observations, (2) student abstract connections to observable phenomenon, (3) student explanations, using their generated models of soils and landforms
investigations to broader physical science concepts such as PNM, (4) reflective practice through the use of science notebooks, and (5) alternative forms of assessing student work. Given the context of model-based inquiry the aim is to answer the following research questions:

1. What semiotic tools (e.g., graphic tools, gestures, representations, verbal and text) do students use to explore, represent and communicate science phenomena?
   a. What do these tools tell us about student sense making of phenomena?
   b. How do students use these tools to interpret their science ideas and observations?

2. What conceptual learning regarding the particulate nature of matter (PNM) seems to occur?
   a. What non-normative conceptions (alternative conceptions) of PNM persist?
   b. How has PNM shaped student sense-making of soils and landforms phenomena?
   c. What soils and landforms conceptions are furthered as a result of incorporating a PNM understanding?

3. Is semiotic analysis a viable tool for understanding student thinking and learning?
   a. Has this semiotic analysis allowed for the creation of useful graphic categories, meaning of categories, and interpreting how students are using graphics to explain science concepts?
CHAPTER TWO
LITERATURE REVIEW

In order to support elementary student model-based inquiry, sensitivity to physical science concepts that are both observable and invisible will be presented in the context of elementary kit-based science curriculum. A means of tying together aspects of the macroscopic observations and microscopic phenomenon is through the particulate nature of matter (PNM). This “Big Idea in science” will be used to bridge elementary science content and inquiry with model-based learning—models, modeling and metamodelling—and student generated drawings to support scientific meaning making. A discussion on the role and use of student science notebooks will follow, since it is a medium to document student science ideas, their strategies to make sense of phenomena, and analyze the various modalities (e.g., graphic, written) used to communicate their ideas. A semiotic assessment tool will be used to describe and analyze student representations created in notebooks within a model-based inquiry structure (Figure 1).

Figure 1: Organizational Framework.
**Kit-based Elementary Science Curriculum**

Elementary science curriculum—the physical and representational tools used in science teaching—is increasingly dependent on a kit-based guided-inquiry instruction to promote science process skills, science content and the nature of science (Forbes & Davis, 2008; Johnston, 2009; Schwarz, Gnuckel, Smith, Covitt & Bae, 2008; Davis, 2006). In the elementary grades guided inquiry includes three phases: pre-investigation where students formulate questions and investigate aspects of the world around them; during-investigation, where students identify, observe and collect data; and post-investigations, where students use their observations to construct reasonable explanations, formulate conclusions, communicate their findings, and evaluate the merits of their conclusions. As a result of this process students are encouraged to identify new lines of inquiry or problems to investigate. By late elementary grades students should be able to recognize the difference between evidence and explanations. This process has been incorporated into a host of kit-based science curriculum and remains an accepted way of engaging students in learning science (Wiebe et al., 2009; Lee, Green, Odom, Schechter & Slatta, 2004; Jordan, 2005). For instance, Ford (2005) focuses on the importance of observation when using Grade 3 kit-based earth science curricula (FOSS, 2000). He suggests that tailored inquiry and literacy practices in the earth science curricula fall short of helping students develop discipline-specific observations. This is because the nature of many of the inquiry investigations had students conduct observations that connect physical manipulation solely to sensory perceptions, resulting in naïve scientific representation of science phenomena.
Jones & Eick (2006) illustrate the challenges of teacher implementation of kit-based curricula. The authors found that teachers were often overwhelmed by the amount of content they needed to cover, and lacked the time to pursue in-depth discussion and the pedagogical content knowledge to effectively implement guided-inquiry. The work of Dickerson, Clark, Dawkins & Horne (2006) investigated the efficacy of implementing a range of earth, physical and biological science kits across Grades 3-5. Findings suggest that students benefit from this active learning approach. However, there remain differences in how to measure student learning based on how the curriculum was enacted. Differences in teacher pedagogical content knowledge, their experience in the classroom, and their science content knowledge can all influence instructional practice.

In a recent study, Wiebe et al. (2009) analyzed the relationship between curriculum-as-written, curriculum-as-enacted, and curriculum-as-experienced. The study coded thousands of student notebook pages over a 2-year period and concluded that science notebooks provided a rich source of information about differences in teacher pedagogical practices, what students were learning, and how notebooks were used. However, additional sources of data (e.g., teacher and student interviews) were needed to identify student sense making of science content. Their findings resonate with those of Dickerson (2006). These studies suggest that kit-based inquiry science can support student science learning. Yet there are few studies linking kit-based curriculum to modeling with the explicit aim of tying invisible and observational science concepts (Wiebe et al., 2009).
The Particulate Nature of Matter (PNM) and Elementary Inquiry Science

PNM helps describe three aspects of our material world that are important to understanding phenomena, including the structure of matter, how it interacts and behaves under various conditions, and its properties. The PNM organizational framework can facilitate pattern recognition and model construction to support student sense making in the physical sciences (AAAS, 2003; Adbo & Taber, 2009; Enfield et al., 2007; Harrison & Tregast, 2002; Stevens, Delgado & Krajcik, 2010). The Soils and Landforms science kit curriculum provides opportunities to leverage an understanding of PNM in explaining the structure, properties, and behaviors of earth material processes—erosion, sedimentation, weathering (physical, chemical, biological) and connect abstract science concepts of gravity, slope, saturation, cohesion, friction, mass, volume, force and pressure (AAAS, 2009; Harrison & Tregast, 2002; Liu & Lesniak, 2006; NRC, 1996; Smith, Wiser, Anderson, Krajcik, 2004).

Over the years a variety of learning trajectories have been proposed to facilitate student learning of PNM. The work by Harrison & Tregast (2002), Liu (2007), Smith, Wiser, Anderson & Krajcik (2006) provide insight into what K-8 students should know prior to entering high school. A) objects are made of matter and exist in different material kinds, b) objects have properties that can be measured and are dependent on the kinds of material, c) matter is conserved, d) matter is transformed, changing some properties and retaining others, e) properties of materials are determined by the nature, arrangement and motion of molecules, f) in chemical changes new substances are formed as atoms are rearranged into new molecules, g) in physical changes, molecules change arrangement and/or motion but
remain intact, the chemical substance stays the same, h) changes occur in everyday matter, i) students can describe and represent matter in a variety of substances. The above trajectory covers many concepts proposed by AAAS (1993) and NRC (1996) for late elementary and middle school students.

Renstrom, Andersson & Ference (1990), Johnson (1998) and Johnson & Papageorgiou (2010) have proposed a substantive framework for understanding PNM. In the case of Renstrom: a) the substance does not have boundaries from other substances and lacks attributes, b) the substance is delimited (empty space) from other substances and exists in more than one form, c) material is made from small particles, d) substances are made of infinitely divisible particles, e) the substance of particles are not divisible into other particles and contain attributes (form and structure), and f) the substance consists of a system of particles that contain macro properties of the substance. In the case of Johnson & Papageorgiou (2010), they propose a PNM trajectory that accounts for two related phenomena a) a substance can be in any of the three known states and b) different substances, under similar conditions, can coexists in different states. This view may provide students with a clearer representational idea on the identities of particles at different levels (e.g, molecules vs. collections of molecules), provide distinctions between substances and mixtures, and support the notion that states of matter are not in themselves different types of matter. Another view that has gained traction is a model of PNM.

Originally proposed by Johnson (1998), a set of models may provide a more general view of how students engage with PNM theory. In many ways, the model captures the learning progression PNM literature, and conceptual constructs students should be able to
grasp throughout a K-12 learning span. Model C is the ideal model, but students tend to experience the earlier models through classroom investigations, prior to developing the ideal or target model of PNM. They are defined as Model X, A, B & C. Model X is when matter is observed as a continuous substance—particles are in contact with each other—and where particle ideas have no meaning at the macroscopic or microscopic level. Model A is still understood as particles as a continuous substance. Particles are drawn, but the substance under observation is said to be between the particles, the particles themselves are in addition to the substance. Model B is when particles are the substance but with macroscopic characteristics. Particles are drawn, perceived as the substance, and there is nothing (empty space) between the particles. Finally, Model C is where particles are the substance and the properties of the state are collective. This is considered a target model, how experts, physical scientist view the particulate nature of matter. In an ideal situation and over many years students should develop a PNM model that implies all matter is composed of discrete, energetic particles that are separated by space (Bucat & Mocerino, 2009; Harisson & Treagust, 2002; Park & Light, 2009; Talanquer, 2009; Renstrom et al., 1990). Research suggests this becomes increasingly important as differences in PNM representational practices influence student sense making of PNM.

Graphical representations of how particles make up material vary; of importance is how particles are imagined under different states. For instance, current practice suggests spacing between solid-solid, liquid-liquid and gas-gas should be about 1:1:10 (Harrisson & Treagust, 2002). Of importance in depicting the difference between solid and liquid is
organization and not spacing, while matter in a gas state might be best depicted by differences in spacing and organization (Figure 2).

Figure 2: Stylized Depictions of Spacing and Organization of Different States of Matter.

Several studies have investigated how students utilize PNM representations to better understand the theory. Sanger’s (2000) research provides evidence that students who were given random drawings—illustrating states of matter (solid, liquid or gas), representations depicting differences in physical composition (pure substance, heterogeneous mixture, or homogeneous mixture), and its chemical composition (those containing elements only, compounds only or both)—were more successful in correctly identifying the particulate drawings. Johnson (1998) noticed students often combined models to reason about substances and that it was possible to change student thinking from a non-normative view of PNM (Model X, A or B) to a normative or target view (Model C) as a result of using student-generated models. An earlier study by Gabel (1993) proposed students’ need to engage in three levels of representation—macroscopic (sensory level), microscopic (atomic/molecular level) and symbolic—in which the inscription is representative but not homologous (not similar to) to the actual phenomena—in order to better understand PNM. Taken together, this
research suggests that developing a robust model of PNM is challenging for students across grades. There are cognitive constraints that must be considered if students are going to make sense of PNM and more importantly apply PNM within broader physical science concepts.

**Student Cognitions and PNM**

Tsitsipis, Stamovlasis & Papageorgiou (2010) suggest several cognitive variables influence student reasoning around PNM, which include a learner’s ability to dis-embed relevant information from complex information. This inability or ability is attributed to the level of information processing skills and capability to work on ill-structured tasks. Another variable is a student’s convergent/divergent thinking skills, seeking a single answer versus generating multiple responses, or a student’s ability to perform logical thinking (i.e. formal-operational reasoning) where meaning is derived from logical relationships within a system. Their findings indicate that cognitive variables have an influence on student understanding and more interventions are typically needed to support student abstract reasoning using diagrams, models and concrete materials.

Additional studies provide some general findings that are worth mentioning. Studies by Talanquer (2009) and Park & Light (2009) suggest students are constrained by their concrete experiences (direct observations) and the contextual and salient features of a system, where students have difficulty determining the important features from its surroundings within a particular context. Often surface level features (e.g., color, size, texture) play a dominant role in student sense making. The complexity of the topic area may force students to develop ritual knowledge—responses based on classroom instruction (Park & Light, 2009). Many young learners lack the flexibility to apply knowledge to novel problems and
struggle to integrate newly formed knowledge structures (Stevens et al., 2010). For instance, once students grasp an understanding of scientific terminology (e.g., density, gravity and friction) they may continue to have difficulty applying these concepts to explaining how soils settle in water. Other studies have provided evidence that students, given the appropriate level of instruction, can think abstractly about PNM starting in early elementary grades (Metz, 1995; NRC, 2007). To gain an indication of where students are in understanding PNM, one must consider broadly their ability to distinguish between compounds, mixtures, substances, solutions, homogeneous matter, heterogeneous matter, solids, liquids, gases, and chemical and physical changes (Gabel, Gall, & Borg, 1987). A more prescriptive approach may help students integrate PNM with other elementary physical science content.

A few studies have introduced PNM with a model-based framework. Andersson (1990) introduced a Matter-Molecules framework to high school students. This method comprised of problem definition, modeling, coaching, fading instructional support, and providing additional resources to further student thinking to elicit student self-explanations. The findings indicated that macro properties transferred to the micro world, models were not separated from the observational reference, and students think additively rather than interactively about the formation of molecules. Often atoms or molecules were depicted as circles, balls and shells, or balls separated by strings and pegs. Smith et al. (2006) suggest that elementary and middle school students use PNM conceptions in conjunction with formal conceptions around models and modeling. These help students to distinguish between properties of objects at the macroscopic level from properties that are more microscopic in nature. Given the right setting, students from an early age can develop epistemological
science knowledge associated with the macroscopic properties of matter (e.g., density and weight) beyond commonsense observations of texture, color and shape. Furthermore, students provided with the appropriate cultural tools, including modeling and science process skills, can develop a rich understanding of matter as having several forms, takes up space, and continues to exist even when broken up into smaller pieces (NRC, 2007).

Using a model-based inquiry (MBI) approach, combining kit-based inquiry curriculum with modeling procedures and scaffolding, students in middle and late elementary can develop a nuanced view of the particulate nature of matter, which then becomes a vehicle to better understanding physical science concepts requiring sense making around invisible science ideas. Examples might be how increasingly smaller pieces of material have weight and impact physical weathering of earth material, or how different soils behave differently in solvents like water. Incorporating MBI along with representations can engage students in investigating physical science phenomena that is the result of the interplay between the macroscopic-microscopic properties while also introducing them to representational conventions of science.

Models, Modeling and Metamodeling

All knowledge of the world is dependent on the ability to construct models—it is a necessary function in both research and the communication of scientific knowledge (Massironi, 2002; Coll, 2005; Henze, Van Driel & Verloop, 2007). Model-based theories are used ubiquitously in the physical sciences to explain causal relationships. Models can be defined as an interpretative description of a phenomenon (object, process, system or event) that facilitates perceptual as well as intellectual access to a phenomenon. It provides a
description that goes beyond perceptual interpretation because it draws upon theoretical background knowledge (Bailer-Jones, 2003; Justi, Gilbert & Ferreira, 2009). Models are artificial, serve a specific intellectual purpose, contain only the relevant information, and are by their very nature imperfect (Gilbert & Watt-Ireton, 2003). They are derived from the mind’s eye facilitating a variety of sense making opportunities. In the past thirty years the science education community has incorporated model based approaches in the area of conceptual change and science instruction (Brewer, 2001). For instance, Abdo & Taber (2009) have worked with 16-year-old students on their conceptions of matter using clinical interviews. They ask students to draw and explain their models, paying particular attention to how students reflect and rephrase their responses. Others such as Khan (2007) have incorporated model-based inquiry to help students investigate chemistry concepts. Students go through a process of building, modifying and critiquing their models. Schwarz et al. (2009) has devised a modeling learning progression to better understand how students construct conceptual understanding. Models support cognitive learning because they are purposeful analogues to the natural world. They are a constructed argument of edited materials presented to explain/explore specific phenomenon. They reflect an aspect of phenomenon that can be characterized, where real-world objects are revealed and relationships drawn (Van Der Valk, Van Driel, De Vos & Wobbe, 2007). Gilbert & Watt-Ireton (2003), Lehrer & Schauble (2006), and Louca et al. (2011) have compiled and defined various model types (Appendix A).

Several modeling ideas are used across a variety of modeling heuristics. For the benefit of the reader these concepts will be defined and referred to throughout this section. A
**mental model** is made up of our sensations and perceptions of the external world and influenced by our memories that often take the form of a mental sketch or percept (Coren, Ward & Enns, 2004; Ware, 2004; Massironi, 2002). They are personal cognitive representations used to instantiate (e.g., reveal) scientific ideas, making them meaningful and memorable to the creator (Johnson-Laird, 1983; Norman, 1983; Brewer, 2001). Gilbert and Watt-Ireton (2003) suggest mental models arise from a schemata—an organized set of symbols—in the form of words, letters and or images to structure our knowledge of concepts.

An **expressed model** is a student’s representation of his or her mental model, which can be constructed from a variety of sources including physical models, paper-based graphic models, animations, photographs, written and verbal explanations, gestures or a mixture of the above (Justi et al., 2009). It is a tool for reflection, aids in conceptual recall, and provides students opportunities to leverage symbolic tools promoting abstraction and generalization of their science ideas (Edens & Potter, 2001). It is a necessary action in order to develop a coherent mental model over time (Lau, Oehlberg, & Agogino, 2009). **Public models** are representations involving small group or whole classroom participation, critical re-representation, trace-overs and/or amendments to the existing model. Making these models public encourages a model base discourse and preliminary evaluation. **Target models** in professional practice reflect consensus of the scientific community at large. Even though these models acquire a sense of permanency in the community, the nature of these models are fluid, as new evidence emerges revisions to the target must be taken into account (Louca et. al., 2011).
What is missing are the revised models individual students create and document for their own learning as a result of engaging in modeling activities. It is a model that can be evaluated and critiqued by the teacher. A Personal Model is a student’s work during various phases of the modeling processes, which may or may not be influenced by classroom discourse, wherein the final decision on the content, organization and composition of the model rest solely with the student. For our purposes, the science classroom community is the expert community.

The iterative and recursive nature of modeling exposes students to meta-representational practices that encourage an understanding of the conventions of science. It is an opportunity for students to translate and manipulate representations at a variety of levels—macroscopic, microscopic and symbolic—encouraging scientific meaning making about cause and effect. It also encourages prediction and alignment of drawings with observation and measurement, providing an opportunity to integrate their experiences into a coherent whole. Thinking with and about models (metamodelling) also prepares students for future learning by identifying key features to attend to and challenges in using models for learning. Awareness of modeling enables students to effectively plan and evaluate their investigations. Schwarz, Reiser, Davis, Kenyon, Achér, Fortus, Shwartz, Hug & Krajcik (2009) discuss the power of students engaged in revising, evaluating, using and constructing models to elaborate on ideas, discern patterns, and predict phenomena respectively. It is a more reflective means of developing scientific reasoning in order to make sense of phenomena. Finally, metamodelling and modeling in general facilitates student discourse, the construction of arguments and explanations to support their claims or position with evidence.
(Ainsworth, Prain & Tyler, 2011; Justi et al., 2009; Lehrer, 2006; Maia & Justi, 2009; NRC, 2007). This circular process is of great benefit to students engaged in inquiry science. The act of modeling is an epistemic function as it reinforces the importance of knowledge as contextualized, specific to a situation, and subject to change as new evidence emerges.

Used effectively, modeling can integrate three aspects of inquiry—science content, science process skills and nature of science—all of which are important to elementary science learning. At each step of the inquiry process, students are building, testing, evaluating, revising, and communicating their science ideas through models (Gilbert & Watt-Ireton, 2003; Justi et al., 2009). The act of modifying a model encourages students to attend to functional aspects of a system and over time show the relations that affect a system’s behavior (Lehrer & Schauble, 2006; NRC, 2007).

The following are several model-based pedagogical approaches used in science and engineering to elicit student sense making. In Model-Eliciting Activities (MEAs) students are engaged in an iterative process of a design-test-revise cycle in order to develop richer explanations and problem solve (Miller, Moore, Self, Kean, Roehrig & Patzer, 2010; Moore, Self, Miller, Hjalmason, Zawojewski, Olds, Diefes-Dux & Lesh, 2010). The Models and Modeling Perspective (MMPS) is used in the creation of structured representations of complex systems to support student collaboration and connection between various types of knowledge (Hamilton, Besterfield-Sacre, Olds & Siewiorek, 2010). The Model of Modeling (MoM) framework proposes a 7 stage iterative process, whereby students: (1) identify the purpose of the model, (2) produce a mental model, (3) express their model using a variety of modalities, (4) conduct a thought experiment to test their model internally, (5) design and
perform empirical tests, (6) determine if the model has fulfilled its purpose by identifying its scope and limitations, and (7) decide to reject or modify the model. This framework captures many of the above approaches by emphasizing the cyclical nature of model-based learning, the importance given to model construction being intentional, and the need to verify the quality of the model through internal and external testing (Justi et al., 2009). Too often studies focus on the product of learning through pre-post test and questionnaires, where the emphasis is on the design and instructional pedagogy at the expense of understanding the student learning strategies (Clement, 2008; Maia & Justi, 2009). A model-based pedagogy can provide ample artifacts for formative and summative assessment, but the practice of modeling can also illustrate the changes in student sense making as they pursue their science investigation. Recognizing student thinking strategies at discreet points during an investigation can highlight possible instructional scaffolds needed to further student sense making. The power of model-based learning is well documented even though in K-12 the practice of modeling is not without its challenges.

Students from a young age can be challenged in producing models that reflect their ideas and observations. Students may have difficulty with a number of tasks related to models. For instance, it may be hard for a student to interpret a two-dimensional representation into a three-dimensional mental image. Students may struggle to perform a mental operation, such as rotation on the 3D image. Creating a re-representation of the newly visualized three-dimensional image as a two-dimensional diagram could also prove difficult. Other challenging tasks could be to understand the nuances of scientific conventions needed to construct an informed representation or making sense of the microscopic ‘reality’ from a
macroscopic image. Students often struggle to engage with the mental demands of thinking in terms of formulas, symbols, macroscopic behavior and microscopic processes and have difficulty developing a criteria as to how best to represent a testable hypothesis (Ainsworth et al., 2010; Bucat & Mocerino, 2009). The deficiency in these skills could carry long term consequences in many STEM disciplines. The abstract sciences and engineering are dependent on models and visualizations to formulate problems, test ideas, make sense of events, and communicate findings. Rather than shying away from the challenges students face, teachers need to encourage student opportunities to safely engage in representational practices of purposeful model building (NRC, 1996; NRC, 2011). The integration of inquiry and modeling provides opportunities for students to test their scientific ideas through model construction.

Kit-based science is driven by a guided-inquiry framework, and provides students with opportunities to learn a variety of science ideas that are challenging to teach holistically (Ford, 2005). The physical sciences remain a difficult area of learning because of the need to better understand the relations between abstract science concepts (e.g., gravity, force and pressure) and the observed phenomena (e.g., stream table model of flooding) (Jones & Eick, 2006; Wiebe et al., 2009). A MBI framework can provide opportunities to further student epistemic goals—building theories and models that are coherent and testable through observation (Gilbert & Watt-Ireton, 2003). MBI is a dynamic learning process where ongoing revision of mental models occurs as part of the process of inquiry (Khan, 2007).

During MBI, students first generate model construction to help instructors parse out what students know and the nature of students’ misconceptions. This information is shared
and discussed with teachers and peers. The alternative or ill-understood conceptions are the basis of students designing their own investigations, or at earlier ages providing guided inquiry investigations. Once the investigations are complete, students revisit, edit or modify their models based on new discoveries (Neilson et al., 2010). As a result of this inquiry experience students develop skills that promote scientific model building, including the controlling and measurement of variables, formulating hypothesis, conducting experiments, and interpreting data (Gilbert & Watt-Ireton, 2003). Student constructed models reveal students’ previous science ideas and provide evidence of student thinking over the course of time. Finally, MBI should help students generate new lines of inquiry (Justi et al., 2009). However, pedagogical challenges remain for how to facilitate student thinking around processes and mechanisms that underlie invisible phenomena.

The kit-based curriculum provides ample opportunities to showcase student science process skills and science content without providing explicit strategies to illustrate the relationship between observable phenomena and the underlying processes (Dickerson et al., 2006). Often, teachers do not have enough time to cover the entire science curriculum, making trade-offs between core science content that may serve students long term and what is attainable during a particular time-constrained science unit (Jones & Eick, 2006). Integrating PNM, modeling, and inquiry science could focus instruction on a few core science ideas. These could have broad implications for student sense making within and across science units, thus giving students the opportunity to develop more robust conceptual framework of key topics. Ideally, a central aspect of inquiry science is meaning making (NRC, 1996, NRC, 2011). Students need access to science learning tools, as a way to
investigate concepts and deepen scientific thinking (Andersen, Scheuer & del Puy Leonor Echverria, 2009).

**Science Notebooks**

Notebooks are a set of entries based on a specific structure encompassing terms, definitions, observational data, descriptions of results, discussions, and personal reflections. (Aschbacher & Alonzo, 2004; Ruiz-Primo et al., 2004; Wiebe et. al., 2008). They are used across a variety of disciplines. Lau et al. (2009) indicates that design journals in industrial engineering provide students with opportunities to sketch their thinking far more than in engineering and science disciplines, encouraging visual ways of thinking that often compliment textual recording of ideas. Svarovsky & Shaffer (2006) and Ekwaro-Osire & Oromo (2007) see engineering journals as a place to support students’ development of epistemic frames—a set of skills, knowledge, values, and epistemology—of a particular profession, and of epistemic practice—ways of thinking about ideas.

This thinking about the use of notebooks in professional practice is in keeping with school-based science notebooks, which are used to document the stages of inquiry, encourage various forms of literacy, and support student scientific thinking (Mintz & Calhoun, 2004). Wiebe et al. (2008/2009) view student notebooks as a cultural tool to promote a variety of epistemic discourses in the form of explanation, argumentation and metacognition. In effect, it is a medium to scaffold conceptual growth through student written/graphic representations over the course of their science investigations. Assessing student science notebooks for their generative responses, conceptual understanding, and ability to communicate their ideas remains central to the role of notebooks in inquiry science. A recent study by Ruiz-Primo, Li,
Tsai & Schneider (2010) reviewed six classrooms of notebooks and found many student explanations where incomplete and fragmented. However, the study was able to show that it was possible to obtain student understanding from what they write in their notebooks. Aschbacher & Alonzo (2004/2006), Butler & Nesbit (2008), Ruiz-Primo et al. (2004), and Wiebe et al. (2009) emphasize the importance of professional teacher development to support student sense making of science ideas. Otherwise, students are left with science knowledge that is in pieces, incoherent and fragmented. In much of the literature on science notebooks and assessment, there remains an emphasis on traditional forms of literacy (e.g., reading and writing) over graphic literacy (Wiebe et al., 2009). The use of multiple representations and student-generated models might help students make sense of underlying science ideas that could inform their surface level observations. More importantly, combining traditional literacy practices with graphic literacy may conjure new student thinking that has been difficult to access via purely written form, such as answers to laboratory questions.

Science notebooks remain a powerful tool for students to document their science ideas, reflect on the content, process and nature of their science investigations, and are a powerful tool to support student sense making (Ruiz-Primo et al., 2010). Kit-based inquiry science remains at the heart of elementary science education reform, where science process skills and literacy are emphasized (NRC, 1996). The lack of instructional time continues to short change student science experiences surrounding, for example, the shaping of the Grand Canyon as a result of erosive forces and properties, because the scale of the phenomenon is
beyond our immediate perception and the geologic change over time associated is hard to imagine.

If a primary goal of science is to support student theory building of science phenomena, then cultural tools and practices (e.g., science notebooks and scientific model building), and ways of accessing invisible science constructs using PNM, may facilitate better integration of science concepts and student sense making. Modeling tools, along with a MBI framework, can play a significant role in shaping student thinking.

Not all representations are models but all models are a form of representation. For instance, models and modeling are purposeful, intentional and over time map to agreed upon scientific conventions and theories, whereas artistic representations are valid in the imagination of the creator and observer without the need for normative scientific scrutiny. Student generated models are tied to the practice of meaning making with signs—the triadic relationship between the referent or object, (such as a river bed), the sign-vehicle (symbols such as arrows, and particles) used to recreate the phenomenon, and the interpretant, (the individual student). In semiotics this triangular relationship is considered central in sense making. Semiotics can be used as a process to analyze and assess the student generated models in the context of scientific meaning making.

Semiotics

The Saussurrean and Peircean approach to semiotics are recognized as foundational in semiotic theory. Saussure viewed signs from a structuralist lens, where the emphasis was based on the autonomous, modular study of meaning structures. Language was at the center of what he coined semiology—signs being part of social life. In this tradition, semiotic
systems were considered autonomous wholes, making it difficult to understand communication between semiotic systems—cultures, scientific paradigms—and other human systems.

A second aspect was that all forms of semiotic phenomena, such as pictures, could only be understood through a linguistic paradigm. As will be understood later, language is one of many sign types that can be used to interpret phenomena. Finally, Saussurean structuralism—that all signs are conventional—made it difficult to understand signs involving iconic components such as maps, diagrams and photographs. Saussure acknowledged that expression could come through a variety of interactions with objects, but the most important relationship in determining meaning came between the dyadic relationship: the sign vehicle, the representation used to carry meaning, and the interpretant, the meaning of the concept the sign refers to (Cobley, 2010; MacEachren, 2004; Ware, 2004). Saussurean structuralism is in contrast to Peircean pragmatism, where semiotics and logic are intertwined to develop truth-preserving inferences using signs and, in the broader sense, the study of science (Cobley, 2010). What follows is a description of the Peircean model, where meaning is developed within a triadic relationship and encompasses a number of sign components,

First, Peircean semiotic reasoning is accomplished within a triadic model between the referent, sign-vehicle and the interpretant. Han & Roth (2005), Cobley, (2010), van Heusden (2009), Hoopes (1991) and Deloache, Peralta de Mendoza & Anderson (1999) elaborate on this triadic model in the following way. Sign making is seen as cognitive process of organizing a suite of semiotic resources. It produces a certain idea in the mind, which also
contains a material quality, carrying properties and relations similar to the object being referred to. The sign carries a dual reality both object and representation of something other than itself. Second, the triad model—referent, sign-vehicle and interpretant—acknowledges a variety of sign components—iconic, indexical and symbolic. This model is consolidated through the work of MacEachren (2004), Ware (2004), and Semetsky (2010), where an iconic sign refers to their object by means of their similarity, quality or description (e.g., diagrams, photographs and maps) and maintain its character even if its object has no existence. Indexical signs refer by means of their connection (i.e., pointing) to their object. They lose their properties if the object is removed or is no longer the point of reference. Symbolic signs are learned-habits, conventions or laws often agreed upon by a community of learners (e.g., an arrow may refer to either a direction of movement or a force). Symbolic signs lose their character if there is no interpretant, they are imbued with meaning by its user. Third, Peircean semiotics is not bound in the strictest sense of the term to language as the way to interpret phenomena. Other sign types, including gestures, can express and convey meaning in ways that language may be less capable of doing. For these reasons, a Peircean model becomes a more fruitful framework to understanding how signs are used in abstraction. The power of signs and sign making is how they can be used to mediate scientific thinking and reasoning—to go beyond information given (Tversky, 2005).

**Signs and Reasoning**

One of the central benefits of sign use is in the development of reasoning strategies that promote scientific thinking and learning. Many empirical studies have connected inductive, deductive, abductive, causal, analogous, and diagrammatic visuospatial reasoning
to abstracting with signs (Coble, 2010; Holyoak & Morrison, 2005; Johnson-Laird, 2005; Dunbar & Fugelsang, 2005; Tversky, 2005; Stjernfelt, 2007). Briefly, inductive reasoning provides students with the opportunity to take their current state of knowledge to novel conclusions. A central feature of models is to increase semantic information in this way, since models are intentionally designed to make sense of phenomena. Deductive reasoning allows students to draw out conclusions that are implicit in their beliefs (i.e., premise) through the use of evidence such as diagrams and mental experiments on diagrams. Abductive reasoning is when thinking leads to explanation. It is dependent on causal relations, which is often used to generate models to resolve inconsistencies in understanding. The process involves the use of incomplete observations followed by developing the most plausible explanation (Jaipal, 2009). This was an important tenet of Peirce’s work (Johnson-Laird, 2005). In causal reasoning, the student is interested in the chain of events that lead from cause to effect. The use of visuals and diagrams become a useful way of representing causal mechanisms, as well as the basis for developing predictions that can lead to new investigations. Analogical reasoning involves students’ systematic correspondence (mapping) of their current information, labeled as the source, to their understanding of the phenomenon, labeled as the target. This form of reasoning is identified closely with helping to make new inferences about the target and seen as a strategy for scientific discovery and conceptual change. Peirce’s development of diagrammatic reasoning is foundational to model theory and model-based reasoning. He considered models to be iconic since they contain a token for each referent in the discourse and embodied properties and relations that correspond to the referent (Johnson-Laird, 2005). Diagrams are useful in instilling mental
models by abstracting the essentials elements and relations associated with the target (i.e., phenomenon), in supporting both structural and functional features of a system or phenomenon, and considered a form of cognitive schemata used in guiding perception, thought and action. These elements are often accompanied by ‘extrapictorial’ devices such as arrows and frames to further meaning making in the form of temporal or causal sequence. Lastly, visuospatial reasoning is considered foundational for more abstract knowledge and inferences. It promotes categorization, conceptualization that might have a prelinguistic basis, as well as problem solving and other reasoning strategies mentioned earlier. An awareness and purposeful use of signs’ semantic, pragmatic and syntactic role in shaping meaning may facilitate richer student science learning experience. A more intentional use of semiotics may help reveal, challenge and further student understanding of the relationship between science concepts, process skills and the nature of science and meaning across modalities. Students remain challenged as how to integrate the various sign resources used to shape understanding. Familiarity with the nature of representation, the science domain, age and cognitive style all impact how students incorporate signs across multiple modalities (Jaipal, 2009). Educators would benefit from a greater awareness of sign use in inquiry based science instruction, since science learning is dependent on a variety of modes/sign types to communicate meaning.

Signs, Learning and Modalities

As pedagogical agents, teachers facilitate student learning in combination with multiple semiotic modalities (e.g., graphics, gestures, written, verbal) (Kress, Jewitt, Ogborn & Tsatsarelis, 2001; Lemke, 1998). Students, in turn, are asked to incorporate teacher-
generated signs, the concept or phenomenon under investigation and other semiotic resources to develop their understanding of the phenomenon. Evidence of their understanding is revealed in their science notebooks in the form of text and graphics, and verbal explanations among peers and teacher, which often incorporates some embodied manifestation of their experience in the form of a gesture. Specific modal communications can favor temporal/sequential characteristics often found in speech, spatial characteristics evoked in graphics, or in the case of gestural communication, all three characteristics might be evident (Kress et al., 2001). Each communication provides trade-offs and benefits individually, but combined may better serve student communication.

For instance, some gestures are considered an indexical component of a sign, it can link verbal and graphical information used to describe and action or add emphasis (Semetsky, 2010; Ware, 2004). Gestures can decrease misunderstanding, since they may be better than words at expressing variation of speed, size, complex relationships of shape or relative position (Lemke, 1998). It is often the case that modes are co-present, where a particular mode can take precedence (in the foreground), play a secondary (background) role to the overall communication or extend thinking when one mode is insufficient in completing an idea. For instance, a gesture might be better at communicating the three-dimensional characteristics of a landform more effectively then speech (Kress et al., 2001). While gestures are a rich form of communication, text or words may still be better at conveying abstract, procedural and conditional information. In a complementary fashion, the integration of text-image information reduces cognitive load, while text-labels can influence how information is encoded (Ware, 2004). A student’s written work supports critical thinking,
promotes convergent thinking, and encourages communication that is coherent and structured (Ruiz-Primo et al., 2010).

Graphics, represented as a combination of marks (points, line and area), are a pervasive form of scientific and engineering communication (Lemke, 1998; Bertin, 1983). Graphics in the form of drawings, pictures and virtual models can be used to store information about an idea, facilitate human comprehension by inscribing the image in the viewers mind, and used as a vehicle for processing information; for instance, mapping abstract reasoning onto spatial and abstract information (Brophy & Li, 2010; Tversky, 2005). The perceptual variables (e.g., plane size, color, value, orientation, shape and texture) can impact how readers extract, process and make inferences (Bertin, 1983). Graphic representations also serve as analogical models, carrying characteristics and spatial relations similar to what it represents (Mayer, 1993; Lehrer & Schauble, 2006). Semiotic systems are unstable and are undergoing constant transformation by the user. Yore & Hand (2010) suggests that how students make sense of multimodal text—the integration of semiotics, semantics, visuals, and sign systems have been somewhat documented—requires greater consideration of learner-constructed representations and multimodal text. There are differences in how students come to know, as it relates to making meaning with representations and making meaning of representations—this study is interested in the former. Semetsky (2010), Kress et al. (2001) and Lemke (1998) discuss how semiotic systems contribute to the function of interpreting multimodal communication. First, in a representational role, they serve in the interpretation of an object or phenomena by signifying observable properties, assigning value judgments (appraisal) and or directing attention to
spatial/temporal dimensions (indentification). Second, in an epistemological role through the creation of knowledge using the strategy of hypostatic-abstraction (Sternfelt, 2007)—creating a new sign for a new object by transforming a concrete idea into an abstraction or thought—is seen as a way of organizing knowledge, a means of generalizing, seeing similarities and differences, classification and establishing a series of logical relations. Third, semiotics has a volitional role, the need to manipulate an aspect of one’s internal or external world induces critical reflection, initiating a form of argument. Finally, in a formal function role of using signs transparently, without reflecting on their meaning, this can be considered a form of cognitive economy or cognitive offloading. Taken together, the function of semiotics is a way of representing, framing and organizing an idea to make sense of phenomena. It informs learning by continually drawing relationships between the form (signifier) and meaning (signified). Hence, meaning can be defined as ideational, interpersonal and textual—a representation of the phenomenon, that is negotiated among a culture of peers and increasingly contextualized (Lemke, 1998). The hybrid nature of classroom scientific discourse requires an approach that takes into account the complexity of student learning.

Semiotics and Assessment

This conceptual framework includes a variety of pieces considered important to student learning. We suggest semiotics can be used as a way to assess student work in the context of using kit-based inquiry science, PNM, MBI, and science notebooks. Kit-based inquiry science relies on a range of discourse and sign use to convey conceptual understanding. Pedagogical scaffolds are needed to facilitate student learning that intersects the observable and invisible world. Ford (2005) suggests students’ drawings are primarily
sensory driven. Jones & Erick (2006) emphasize teacher’s lack time and resources in order to fully implement inquiry-based science. Wiebe et al. (2009) identified the need for additional assessment of student work across modalities. The STC (2010) and FOSSweb (2008) provide a number of abstract science concepts but pedagogical tools are still lacking. Incorporating semiotics as an assessment tool could provide insight into the importance of integrating Pierce’s triadic model to encourage more meaningful understanding of observational drawings. It can also be used to triangulate student epistemic discourse in notebooks and self-explanations.

Students experience a variety of challenges representing and reasoning about the PNM (Tsitsipis et al., 2010; Johnson & Papageorgiou, 2010; Renstrom et al., 1990). Because semiotics fosters multi/meta representational practices it can be used to compare student-generated models as a process of meaning making. It is also a holistic way of critiquing representations on the basis of their structural and functional meaning. Students will be using several semiotic tools—Particle, Magnifer, Vector, Frames—in the creation of their work. Assessing how these tools foster meaning making is an important aspect of this study. The need to provide a variety of scaffolds for students will be informed by how well these tools support student sense making.

Models are considered purposefully constructed explanations, arguments and or descriptions of phenomena (Justi et al., 2009). They can include graphic marks, symbols, written text, utterances, gestures, physical materials, analogies, empirical data, list of assumptions and propositions (Bailer-Jones, 2003; Hamilton, Lesh, Lester & Brilleslyer, 2008; Schwarz et al., 2009; Schmucker, 1998). Student constructed scientific models that
pertain to causal relationships in the physical world may be best understood by looking at the structural components that make up a scientific model in professional practice. Louca et al. (2011) proposes assessment of representations of physical systems that might be best understood by identifying the components of a model in both theoretical and mathematical terms. This includes the physical objects, the primary pieces in the physical system that are directly tied to the systemic structure. These can be defined as the internal objects that play a functional role in the mechanism underlying the phenomenon, and the external objects that do not play a role in the mechanisms underlying the phenomenon. For instance, the internal objects of a stream table investigation include water and soil. While the external objects might include the physical stream table. In addition to the physical entities, there are also abstract science concepts, invented by the human mind in order to interpret physical phenomenon. These are often in the form of symbols to represent concepts of gravity, PNM, and velocity. The objects behavior, in turn, is often considered through the causal relations among physical entities. For instance, how the rate of erosion is affected by material earth properties and the volume of water used in the investigation. The interactions between physical objects, physical entities and objects’ behavior provide a more holistic view of the phenomenon. Finally, the accuracy of the model depicting the phenomenon goes beyond aesthetic properties. This might include attributes of a scientific model described by Halloun’s (1996) and Neilson et al. (2010) criteria, where they stress models as representative of a domain, and must show mechanisms and causality, can be used to predict phenomenon, must be well organized, and finally, understandable. The cognitive processing and skills needed to generate robust models remains challenging to novice and experienced
users. Because of the recursive nature of modeling and the emphasis on discussion and collaboration, a semiotic discourse assessment tool can explore student explanations across a variety of modalities and model types (e.g., personal and public), and analyze student work in the context of how signs are created to make meaning.

A primary purpose of models is to facilitate student explanations of natural phenomenon. The role of scientific reasoning in science education is documented in Osborne (2010) which includes: identifying patterns in data; coordinating theory with evidence; constructing evidence-based explanatory hypothesis or models of scientific phenomenon, and persuasive arguments; and resolving uncertainty through the exploration of large bodies of science knowledge through science inquiry methods. A prominent goal of reformed based elementary science education is to promote student explanation of science phenomenon (AAAS, 1993; NRC, 1996/2007). Braaten & Windschitl (2011) document how traditions of scientific explanations in science education are used as explication, definition of terms requested by the teacher; simple causation, where the emphasis is on cause-effect relationships; and justification, the construction of an argument—which usually takes the form of claim—evidence, and reasoning moves. What may be important is evaluating student explanations along a continuum. That is, student explanations can be framed along a what, how and why progression. What responses entail a description of what happened, in the form of summarizes or restatements without making connections between observable and invisible components of phenomenon. How responses are partial descriptions of phenomenon and address observable and invisible aspects tangentially. Why responses, address why a phenomenon occurred, trace causal relations, incorporate additional sign resources and
leverage powerful ideas in science like (PNM) to explain observable events. This explanation progression might also be useful in aligning aspects of socioprofessional practice to science education.

Lastly, the range of content in science notebooks is often created and organized in a segregated manner, making it difficult for students to draw connections (Wiebe et al., 2008). Semiotics can go beyond traditional ways of focusing on student written work and the aesthetic value of their drawings by analyzing their graphics in terms of meaning across a variety of communication dimensions. Assessing student insights or inferences through a range of modalities and sign systems requires students be given the opportunity to communicate their thinking. Jaipal’s (2009) work on multimodal semiotic discourse analysis with teachers provides a direction on how to assess students sense making of observable and invisible phenomena related to earth material behavior. The author leans on Lemke’s (1998) work in describing four dimensions of semiotic meaning: presentation, capturing the conceptual aspects or descriptions of meaning and signs used to represent the phenomenon; orientation, the social aspects such as classroom interactions and signs used to communicate ideas; the organizational component including the curriculum and graphic representations used in the curriculum; and the epistemological function, the nature of knowledge creation as a result of reasoning and the interplay of modalities.

The nature of semiotic discourse—the use of signs across modes, best captured across a variety of mediums—may require an analytical approach that is sensitive to the mode and medium used to capture student sense making. Brenner’s (2006) discourse analysis process—transcription, description, analysis, interpretation and data display—is sensitive to what is
transcribed, how the transcription is coded, the comparisons of student responses across informants in similar context, and how a combination of verbatim quotes, mini cases and graphical representations of student discourse may better communicate findings. Bloome & Clark (2006) and Erickson (2006) are sensitive to capturing a broad range semiotic tools and inscriptional practices and consider the play and replay of video tape, transcribing talk, documenting gestures as part of a critical and reflective practice of using video as a resource but not data per se. By comparing and revisiting the data provides for molar coding of student thinking.

It is not simply documenting discourse across modes that is important, but the need to analyze student explanations and their use of signs at various junctures of learning. Louca’s et al. (2011) work on modeling physical systems and Halloun’s (1996) dimensions of a model: the domain, the overall physical system, object or referent; the composition, the context and sub-content associated with the model; the structure, including its geometry, and how it interacts and behaves within a certain physical system; and its organization, the principals, laws and rules governing the model. Along with Jaipal’s (2009) analytic framework, Lemke’s (1998) and Kress et al. (2001) ideas around semiotics functions for communication will be used to design an assessment tool to make sense of student’s elicited explanations.
CHAPTER THREE

METHODOLOGY

Research Questions 1 & 2, listed below, was explored using a Science Learning Trajectory Assessment Instrument that integrated student sign use across a range of modalities to reveal students’ understanding of physical science concepts in conjunction with PNM. This was accomplished by mapping student self-explanations—documented in class and in one-on-one sessions with the researcher—along a progression that moved from descriptive responses to explanations that described and explained the causal nature of phenomena. Student notebook entries were used to elicit student reflection and provided evidence of their current state of science understanding. The assessment tool provided a structure to document the semiotic resources used in student self-explanation and document student thinking of invisible science concepts through a PNM lens.

RQ1: What semiotic tools (e.g., graphic tools, gestures, representations, verbal and text) do students use to explore, represent and communicate science phenomena?

   a) What do these tools tell us about student sense making of phenomena?

   b) How do students use these tools to interpret their science ideas and observations?

RQ2: What conceptual learning regarding the particulate nature of matter (PNM) seems to occur?

   a) What non-normative conceptions (alternative conceptions) of PNM persist?
b) How has PNM shaped student sense-making of soils and landforms phenomena?

c) What soils and landforms conceptions are furthered as a result of incorporating a PNM understanding?

This holistic mixed method multiple case research study—multiple sites and sub cases—(Crewell & Clark, 2007; Yin, 2009) was focused on aspects of student cognition, using model-based inquiry (MBI) and the particulate nature of matter (PNM) as semiotic resources to engage students in physical science phenomena. Descriptive statistics of student sign use across modalities coupled with student scores from the *Science Learning Trajectory Assessment Instrument* accounted for the quantitative data, while student self-explanations across modalities was the basis for qualitative case analysis. Both types of data were used to assess students’ meaning making of soil science phenomena (Figure 3).

![Data Triangulation Design: Convergence Model](Creswell & Clark, 2007)

Figure 3: Data Triangulation Design: Convergence Model (Creswell & Clark, 2007).

It was assumed that sense making was the result of the interplay between the invisible and observable world. It was a multi site (2 schools, 2 classrooms) with sub cases, whereby individual student evidence-based explanations in the form of open ended and semi-
structured interviews was collected and compared (Brenner, 2006; Yin, 2009). The unit of analysis was individual Grade 3 & 5 students in two schools in the same district in the Southeastern United States. The main study was preceded by a pilot study of a Grade 5 Landforms science classroom in which there was a researcher-observer relationship between the researcher and elementary science teacher. The major steps included:

Stage 1: Pilot Study – Developed nonintrusive classroom interaction protocol. Refined an open ended and semi-structured interviewing technique. Created a data collection protocol to capture classroom interactions. Introduced modeling tools during specific investigations. Collected, photographed and scored science notebooks.

Stage 2: Recreated select student notebooks and conducted Grade 5 pull out interviews.

Stage 3: Grade 3 classroom intervention – Designed and modified the soil science curriculum. Introduced and scaffolded modeling tools during specific classroom investigations. Collected, photographed and scored science notebooks.

Stage 3: Recreated student notebooks and conducted pull out interviews.

The researcher was interested in sites that provided ongoing science instruction, that reflected typical elementary urban/suburban student body, and provided a range of student scientific discourse opportunities (Bogdan & Knopp Biklen, 2007).

Participants

Both elementary schools were located in the Southeastern United States in the same Urban/Suburban district. The Grade 3 (N=22) and Grade 5 (N=30) classrooms were of mixed ability and mixed ethnicity. The basis for school selection was the Graphic Enhanced
Elementary Science (http://gees.fi.ncsu.edu) research study conducted with six area schools. Previous relationships with teachers in the schools provided an opportunity to recruit teachers and design new research questions. The students who participated in the study were based on a criterion sampling. Internal sampling criteria was based on (a) teachers engaged in elementary science, (b) where science teaching and learning occurred three times per week, (c) student willingness to participate in the study, (d) notebook availability, and (e) student willingness to be interviewed during and after classroom instruction. The pilot study (Grade 5) was 50 minutes/3 times per week over 3 weeks covering two topics (erosion and deposition), while the full teaching experiment (Grade 3) was 35 minutes/4 times per week, over 9 weeks, covering 7 topics (Bogdan & Knopp Biklen, 2007) (Appendix F).

**Context of the Study**

Both grades received kit-based science instruction. The Grade 5 teacher received beginners and advanced training in kit-based science and science notebooks from the local school system (http://gees.fi.ncsu.edu). The Grade 3 teacher received general training in the use of science notebooks and kit-based science curriculum from the local school system (http://gees.fi.ncsu.edu). The Grade 5 students received science instruction for 36 weeks/3 times per week/50 minutes covering four different kits, while the Grade 3 students received instruction for 36 weeks/4 times per week/35 minutes covering four different science kits. Students received science instruction from Grades 1-5 consistently throughout the year but the amount of time and number of days devoted to science varied based on grade, school culture and teacher experience. The interventions focused on the overlay of kit-based physical science concepts with model-based inquiry methodology and PNM as the
overarching big idea. The aim was to elicit student self-explanations during and after MBI instruction. Changes and or modifications to pedagogical approaches were informed by the student voice, interviews and interactions over the course of the science investigations.

*Landforms Physical Science Content*

The Full Options Science System (FOSSweb, 2008) Grade 5 Landforms curriculum was divided into five investigations: (1) the making of a 3D physical model of a school yard and its subsequent translation into a paper-based map; (2) the construction of stream tables to investigate erosion, deposition and stream flow; (3) the manipulation of variables (e.g., slope and rate of water flow) to further student understanding of the impact of erosion and deposition on landforms; (4) the opportunity to build a 3D model of a mountain, develop a profile view of the model mountain and relate topographic features to symbolic representations on geological maps; and (5) extend student understanding of topographic maps to authentic geological maps from USGS. The teacher section of the curriculum unit provided an overview of the abstract science concepts that connected to the science investigations. These included gravity, a force of attraction by which objects tend to fall towards the center of the earth; slope, a change in elevation; saturation, the maximum quantity of water air can hold at a given temperature or pressure; friction, a force that results from relative motion between objects; mass, the amount of matter an object has; force, a push or pull; and pressure, the force acting on a surface area. Not surprisingly, there were direct connections between the Landforms and Soils kits that were of interest to us.
**Soils Physical Science Content**

The Grade 3 STC (2010) Soils curriculum contained 16 investigations which can be grouped under five themes: (1) composting, the breakdown of organic material into humus; (2) properties and behavior of soil types (Sand, Clay and Humus); (3) mystery soil, using inquiry to identify soil types; (4) the relationship between plants and soil; and (5) exploring the local soil. The abstract science concepts mentioned in the Soils unit included: gravity; saturation; properties (e.g., crystal like structure); density, the ratio of mass to volume; weight, a force created by gravity; and the particulate nature of soil (e.g., cohesion, conservation of matter, and change in matter). What remained elusive were the specific pedagogical strategies for student reflection (e.g., textual, verbal and graphical) that were effective in promoting student sense making of macroscopic phenomena such as erosion, and microscopic properties of soil particle behavior to explain earth material processes, structure and behavior under different conditions. To access earth material processes at various levels of abstraction may have required metarepresentational practices—thinking in terms of a model based recursive and iterative inquiry process—to connect the concrete and abstract world of nature’s materials. But good modeling practice may also have required a rich science content that speaks to the ways nature organizes itself. A particulate nature matter (PNM) model could have supported young learners in grappling with the macroscopic and microscopic worlds because it provided a way of supporting a host of science concepts that can be explored and explained through this theory.
The Role of the Teacher and Researcher

The researcher often acted as a participant-observer, since it was an effective way of observing students involved in a variety of classroom interactions—students responding to predefined objects (phenomenon), as interpreters, definers, signalers, and symbol and signal readers, and whose behaviors or meaning was best understood through the researcher engaged in this process (Bogdan & Knopp Biklen, 2007). The researcher-teacher interactions included agreement on the physical science concepts, a review of model-based inquiry and teacher-student interview opportunities. During the initial course of the interventions, the researcher observed the classroom taking field notes. By the third day of teacher instruction, a video camera was placed in the room to help acclimatize students to being videotaped. Initial observation and placement of the camera insured a diffusion of power differential (Brenner, 2006), ensuring students were comfortable with the researcher’s presence and interactions. There were several opportunities for the researcher to act as a facilitator/science resource and co-teach while the camera captured student activity. On other occasions, the teacher lead instruction while the researcher observed and participated in student discussion, probing students with open-ended questions. The researcher bracketed his/her judgment/opinion in order to follow the student process and product(s) of learning.

Field Procedures

The initial recruitment and field procedures was the same for Grade 3 (full research) & Grade 5 (pilot). The researcher: (1) sent teachers a recruitment letter (Appendix B), (2) organized individual meetings to discuss the study, (3) conducted a follow-up teacher interview on the use of semiotic tools (Appendix C), (4) provided supplemental professional
development materials on MBI and PNM (Appendix D), (5) introduced themselves to the students to solicit participation in the research study, and (6) provided consent forms for the teachers and students to sign (Appendix E). The Grade 5 content covered stream tables, erosion, deposition, slope, glaciers, and experimental design (Appendix F). The Grade 3 content covered garden soil; properties of sand, clay and humus; making coffee as an analogy to erosion and deposition; making mud smears; soil smears; soils’ water holding capacity; how different soil settles in water; and a mystery mixture investigation. (Appendix G)

The pilot study provided the researcher with opportunities to: observe the teacher scaffolding the semiotic tools, co-teach several concepts, introduced analogies (e.g. the making of coffee to discuss erosion) and provided other contexts (e.g. glaciers) to support student sense making around erosion and deposition. The goal was to elicit student self-explanations during classroom investigations and to follow science instruction to see how they integrated invisible and observable physical science phenomena. After preliminary analysis, the researcher conducted a full research study furthering the use of MBI framework, and covering the Soils content mentioned earlier. Each day the researcher, in agreement with the science teacher, provided inquiry activities to support student exploration and thinking about soil properties. The researcher co-taught throughout the full study.

Data Source and Data Collection

The data sources included classroom observations, open ended and semi-structured interviews, field notes, notebook entries, pre-post assessment (Grade 3 only) and pre-post teacher interviews. Specific documentation included:
1. Video recording of whole classroom and small group investigations in context;

2. Video recording of individual, in-class open-ended interviews, where the researcher engaged the informant (student) in descriptive questioning related to the science investigation;

3. Audio and video recording of individual student semi-structured pull out interviews with probes (two to three weeks after the science unit was completed) covering unit specific content tied to their science notebook entries and broader aspects of the science unit. The questions were age-appropriate focused on what, how and why explanations to fully reveal what students know (Braaten & Windschitl, 2011). Probing techniques included detailed probes, clarification probes, follow-up probes, silent probes and encouragement probes to facilitate detailed informant responses (Brenner, 2006).

4. Audio field notes of researcher reflections of investigations in context;

5. Photographs of student science notebook entries;

6. Pre-Post summative assessment combining MBI artifacts, the States Blue Diamond assessment and previous teacher assessment (Grade 3 only); and

7. Audio recording of pre-post teacher interviews.

Table 1 & 2 provide details related to each classroom, a brief description of the investigations, sources of data collection and the procedures for Grades 5 & 3, respectively.
Table 1: Grade 5 Data Source and Data Collection

<table>
<thead>
<tr>
<th>Activity</th>
<th>Description</th>
<th>Protocol</th>
<th>Media</th>
<th>Procedures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erosion</td>
<td>Students investigated how water volume changed</td>
<td>Classroom Interview</td>
<td>P, V, F</td>
<td>Students conducted an investigation, documented observations and provided</td>
</tr>
<tr>
<td></td>
<td>the rate of erosion.</td>
<td>Guide (Appendix H)</td>
<td></td>
<td>explanations.</td>
</tr>
<tr>
<td>Mini-Experiment</td>
<td>Students made coffee and compared the investigation to aspects of erosion and deposition.</td>
<td>Classroom Interview</td>
<td>P, V, F</td>
<td>Students conducted an investigation, documented observations and provided</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Guide (Appendix I &amp; J)</td>
<td></td>
<td>explanations.</td>
</tr>
</tbody>
</table>
### Table 1 (Continued)

| Deposition | Students investigated landform creation and sedimentation carried by water. | Classroom Interview Guide (Appendix H) | P, V, F | Students conducted an investigation, documented observations and provided explanations. |
| Slope | Students investigated how the rate of erosion and sedimentation as a result of changes in plateau elevation. | Classroom Interview Guide (Appendix H) | P, V, F | Students conducted an investigation, documented observations and provided explanations. |
Table 1 (Continued)

| Glacial Students explored physical weathering created by glaciers using stop motion photography. | Classroom Interview Guide (Appendix K) | P, V, F Students conducted an investigation, documented observations and provided explanations. |
| Student Notebooks | Student science investigations were documented in their notebooks. | Student notebooks were used for semi-structured interviews and analysis. | N Student notebooks were collected, photographed and catalogued at the end of the science unit. |
| Student Semi-Structured Interviews | Pull out interviews were conducted 2-3 weeks later. | Individual landforms Interview Guide (Appendix L) | N, V, A Replicas of selected student notebooks were used to accompany 20-30 minute scheduled interviews. |

W= Worksheet; V= Classroom Video; F=Field Notes; N= Student Notebooks; A= Audio Recording
Table 2: Grade 3 Data Source and Data Collection

<table>
<thead>
<tr>
<th>Activity</th>
<th>Description</th>
<th>Protocol</th>
<th>Media</th>
<th>Procedures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pretest &amp; Museum Day</td>
<td>Student explored garden soil</td>
<td>Soils Pre-test (Appendix M)</td>
<td>P, F</td>
<td>Students’ explored local garden soil then completed a written pre-test.</td>
</tr>
<tr>
<td>Part 1: Sand, Clay, Humus, coffee and sponges</td>
<td>Students explored material properties</td>
<td>Observation Worksheet (Appendix N)</td>
<td>P, V, F</td>
<td>Students’ explored different soils, coffee grinds, sponge properties, and documented their observations.</td>
</tr>
<tr>
<td>Part 2: Sand, Clay, Humus, coffee and sponges</td>
<td>Students were introduced to modeling tools to expand on their previous observations.</td>
<td>Observation Worksheet (Appendix N)</td>
<td>P, V, F</td>
<td>The instructor modeled how to use the Particle+Magnifier tool to enhance their observations. Students completed their remaining observations using the new tools.</td>
</tr>
</tbody>
</table>
Table 2 (Continued)

<table>
<thead>
<tr>
<th>Part 1: Making Coffee</th>
<th>Observation Worksheet (Appendix O)</th>
<th>P, V, F</th>
<th>Students were given materials and verbal instructions on how to make coffee.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Students made coffee to explore aspects of erosion and deposition.</td>
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</table>

<table>
<thead>
<tr>
<th>Part 2: Making Coffee</th>
<th>Observation Worksheet (Appendix O)</th>
<th>P, V, F</th>
<th>Diagram and modeling tool were provided to enhance their observational drawing.</th>
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<tbody>
<tr>
<td>Students were introduced to a modeling tool.</td>
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<tr>
<th>Mud Smear</th>
<th>Observation Worksheet (Appendix P)</th>
<th>P, V, F</th>
<th>Students were given the basic ingredients to make mud, complete a smear and incorporated modeling tools to describe their observations.</th>
</tr>
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<tbody>
<tr>
<td>Students were given a list of materials to make a mud smear.</td>
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<thead>
<tr>
<th>Soil Smears</th>
<th>Observation Worksheet (Appendix Q)</th>
<th>P, V, F</th>
<th>Students predicted what soils smears would look like when wet, created and described their soil smears.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Students created soil smears.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Can Soil Hold Water?
Students compared the water holding capacity of various soil types.
Observation Worksheet (Appendix R)

How quickly does soil settle in water?
Students compared how different soils behaved in settling tubes filled with water.
Observation Worksheet (Appendix S)

What is your mystery mixture?
Students were given three mystery mixtures to identify.
Observation Worksheet (Appendix T)

Students created coffee making stations, placed one soil type into each funnel, poured water overtop, described and explained what happened.

Students were given settling tubes, entered a measured amount of soil and water in three different settling tubes, and explained what happened at set interval times and 24 hours later.

Students were given a letter explaining the investigation, provided with tools and resources to conduct soil tests, and completed a small lab report.
Table 2 (Continued)

<table>
<thead>
<tr>
<th>Post-Test</th>
<th>Students completed a</th>
<th>Assessment Instrument</th>
<th>P, F</th>
<th>Students were given a posttest that included questions from the pretest, the Blue Diamond tests, and previous teacher assessment and items from the classroom investigations.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Student Notebooks</td>
<td>Student science investigations were documented in their notebooks.</td>
<td>Student notebooks were used for semi-structured interviews and analysis.</td>
<td>N</td>
<td>Student notebooks were collected, photographed and catalogued at the end of the science unit.</td>
</tr>
</tbody>
</table>

| Student Semi-Structured Interviews | Pull out interviews were conducted 2-3 weeks after the science unit ended. | Individual Soils Interview Guide | N, V, A | Replicas of selected student notebooks were used to accompany 20-30 minute scheduled interviews where students were given the opportunity to elaborate on their student generated models. |
Table 2 (Continued)

<table>
<thead>
<tr>
<th>Group</th>
<th>Modeling</th>
<th>Interview</th>
<th>Group Interview Guide</th>
<th>V, A, P</th>
<th>Three weeks after the Soil unit was completed four students were selected for an hour-long collaborative modeling exercise.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small group</td>
<td>Small group interview during lunch hour.</td>
<td>(Appendix W)</td>
<td>V, A, P</td>
<td>Three weeks after the Soil unit was completed four students were selected for an hour-long collaborative modeling exercise.</td>
<td></td>
</tr>
</tbody>
</table>

W= Worksheet; V= Classroom Video; F=Field Notes; N= Student Notebooks; A= Audio Recording
Data Analysis

In order to address **Research Question 1 & 2** the researcher proposed a *Science Learning Trajectory Assessment Instrument* to capture a range of student semiotic discursive patterns including: the use of signs during MBI instruction to make sense of phenomenon, how reasoning with signs support student explanations of physical science phenomenon that is both observable and invisible, how a semiotic discourse tool supported graphic categorization and revealed student meaning making across a variety of modes, and how following the student voice revealed patterns of semiotic discourse to shape future assessment of student learning. The proposed *Science Learning Trajectory Assessment Instrument* followed the students’ sense making across a range of semiotic strategies, using video resources to document verbal and gestural semiotic discourse (Erickson, 2006). In addition, model based assessment elements were focused on evaluating evidence-based scientific explanations and artifacts during and after the MBI process (Louca et al., 2011; Neilson et al., 2010). The *Science Learning Trajectory Assessment Instrument* was designed to account for the developmental readiness of elementary science students, such that many of the categories associated with student constructed models have been collapsed to better reflect elementary science students, the science curriculum and teacher expectations. The *Science Learning Trajectory Assessment Instrument* was couched in an analysis process suggested by Brenner (2006):

1. **Transcription** of selected student interviews both open ended and semi-structured. A total of 19 students were selected for analysis of their science notebooks and self-explanations.
2. **Description**, the *Science Learning Trajectory Assessment Instrument* was used to score and categorize student explanations. These categories were the basis for developing rich descriptions of student sign use across modalities covering a host of observable and invisible science concepts. The goal was to describe how and when signs were used in student sense making. Examples of student artifacts and self-explanations were mapped using the *Science Learning Trajectory Assessment Instrument* (Table 3).

Table 3: Science Learning Trajectory Assessment Instrument (Verbal + Gestural)

<table>
<thead>
<tr>
<th>Levels</th>
<th>Progression</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Extended</td>
<td>Application of soil science models to natural phenomenon. The interactions between soil material, soil process formation, science mechanisms and environment were used to explain soil science phenomenon.</td>
</tr>
<tr>
<td>4</td>
<td>Advanced</td>
<td>Aggregate view of soil. The interactions between soil material, soil process formation, science mechanisms and environment were used to explain soil science phenomenon. Student traces why something happened by describing causal relations.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td><strong>Table 3 (Continued)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Intermediate</td>
<td>Particle view of soil. Students described partial reference to soil process formation, science mechanisms and or environment interactions. Students described semi-causal relations or how something happened. Students incorporated macroscopic and microscopic view.</td>
</tr>
<tr>
<td>2</td>
<td>Novice</td>
<td>Students’ general perceptions of soils physical, chemical and or biological properties (e.g., texture, structure, plasticity, consistency, color, density, porosity, water relations, organic material, and nutrients). Students incorporated personal experience with phenomenon. They described macroscopic view of soil phenomenon with no causal relations.</td>
</tr>
<tr>
<td>1</td>
<td>Alternative</td>
<td>Continuous view of soil and non-normative explanation of soil.</td>
</tr>
</tbody>
</table>

Informed by (Braaten & Windschitl, 2011; Chappell, 2008; Cobley, 2010; Johnson, 1998; Jones, 2011; Louca et al., 2011; Neilson et al., 2010; Reynolds, 2010 & Smith et al., 2004).
Table 4: Science Learning Trajectory Assessment Instrument (Graphical + Textual)

<table>
<thead>
<tr>
<th>Levels</th>
<th>Progression</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Extended</td>
<td>Application of soil science models to explain phenomenon. Model represented interactions between soil material, soil process formation, science mechanisms and environment. Model approximated target model, was well organized, legible and understandable. Model showed evidence of causal relations between two objects, entities or processes, and contained annotations.</td>
</tr>
<tr>
<td>4</td>
<td>Advanced</td>
<td>Aggregate view of soil particles. Model represented interactions between soil material, soil process formation, science mechanisms and environment. Model was well organized, legible and understandable. Model showed evidence of causal relations between two objects, entities or processes, and annotations.</td>
</tr>
<tr>
<td>3</td>
<td>Intermediate</td>
<td>Particle view of soil. Model represented partial reference to soil process formation, science mechanisms and or environment interactions. Model showed evidence of semi-causal relations, and contained annotations.</td>
</tr>
</tbody>
</table>
Table 4 (Continued)

2  Novice  Students general perceptions of soils physical, chemical and or biological properties (e.g., texture, structure, plasticity, consistency, color, density, porosity, water relations, organic material, and nutrients). Students incorporated personal experience with phenomenon. Model represented macroscopic view of soil phenomenon, incorporated internal (material associated with the phenomenon) and external (material tangential to the phenomenon) objects. Model showed no causal relations.

1  Alternative  Continuous and non-normative view of soil.

Informed by (Braaten & Windschitl, 2011; Chappell, 2008; Cobbley, 2010; Johnson, 1998; Jones, 2011; Louca et al., 2011; Neilson et al., 2010; Reynolds, 2010 & Smith et al., 2004).

Figure 4 was the legend of symbols used to create Figures 5-10, elementary soil science target models.
Figure 4: Legend for the Creation of Target Models

Figure 5: The Particulate Nature of Soil

- Soil interacts with different types of matter (solid, liquid & gas).
- There can be invisible pieces of soil (i.e., too small to see with the naked eye).
- Soil continues to exist when broken into pieces too tiny to be visible.
- The amount of soil and weight are conserved across a range of transformations (e.g., dissolving).
**Figure 6: Properties of Soil**

- **Dry Sand Particles**: Sand is coarse, is the largest particle, has sharp edges, is firm, reflects light, is porous, does not hold water well and dries quickly.

- **Dry Clay Particles**: Clay is the smallest particle, smooth when dry but sticky when wet, made up of fine particles, can be molded, holds water and nutrients but difficult to grow plants in.

- **Dry Humus Particles**: Humus is the smallest particle, dark in color, contains a substantial amount of air, is irregular in shape, and is porous.
Figure 7: Soil Formation and Profile
Figure 8: Soil Saturation

- Saturated Sand Particles: Soil oversaturation is when grains lose grain-to-grain contact as water squeezes between them.
- Saturated Clay Particles: Increased water infiltration reduces pore space in clay, reducing open spaces and causing the clay minerals to flatten.
- Saturated Humus Particles: Abundant pore space allows for the filtering of water yet holds sufficient water for plant growth.
• The three forces responsible for the rate of soil particle movement through water are buoyancy, friction and gravity.
• Soil particle size and density influence particle movement through water.
• The density and viscosity of water vary with temperature, hence the velocity of particle settling is influenced by the temperature of the water.

Figure 9: Soil Settling in Water
3. **Analysis**, identifying emergent patterns of model discourse (verbal/gestural and graphical/textual) to compare similarities and differences in student responses within and across informants across two dimensions of semiotic meaning *Presentation* and *Epistemic* (Jaipal, 2009; Lemke, 1998). A matrix illustrating the patterns of student discourse along these two dimensions of meaning provided insight for interpreting the theoretical implications of this study.

4. **Interpretation**, emergent themes were connected to the larger literature on semiotics, graphics, modeling, and scientific explanations.
5. **Data Display**, integrated quotes, mini case studies and visualizations to communicate findings.

Findings as a result of implementing the *Science Learning Trajectory Assessment Instrument* provided insights into the efficacy of this tool to assess student semiotic discourse and implications for science teaching and learning moving forward. Research Questions 3, listed below, was covered in the conclusion section.

**RQ 3:** What is the efficacy of the semiotic analysis deployed to understand student thinking and learning?

a. Has this semiotic analysis allowed for the creation of useful graphic categories, meaning of categories and interpreting how students are using graphics to explain science concepts?

*Validity and Reliability*

Gall et al. (2003) provided a list of considerations researchers should use when implementing a case study design. Below are the validity and reliability concerns that addressed this study.

**Chain of Evidence:** In order to collect evidence of student thinking and reasoning about science phenomenon, classroom video recordings of student interactions and elicited self-explanations, student notebook entries of their science investigations, the open and semi-structured probative interviews, and pre-posttest were used to construct a holistic view of the students’ understanding of particular science concepts. Brenner (2006) data analysis process ensured data was properly transcribed and categorized and coded to facilitate proper interpretation and analysis. The *Science Learning Trajectory Assessment Instrument* was
used to organize student semiotic explanations along a continuum of meaningful responses that provided a more emergent view of the students thinking and reasoning. Instruments and protocols were developed to facilitate student learning and capture student responses with the aim of developing further insight into how students make sense of phenomenon.

**Interpretive Validity:** The current assessment practice in elementary science education is limited to paper pencil test and general classroom participation. There was a need to develop alternative ways of fully assessing student thinking and reasoning of science phenomenon. The usefulness of this study was in triangulating the student semiotic discourse across multiple modes over a longer period of time. Hopefully, it revealed a richer set of responses that informed future pedagogical practices. Student data was collected in an *authentic science classroom setting*, where materials, inquiry science and semiotic tools were used to further student thinking. The research study did not limit *whole class participation* into the varied science investigations even if students did not permit interviews or analysis of their science notebooks. Many of the science investigations were modified but with the intent of engaging students in rich science experience that is developmentally appropriate. Students were not intimidated by the additions or modifications to the science curriculum since they were accustomed to participating in science investigations regularly. The modifications were not disruptive to the learner and were within their *regular science classroom schedule*. This study encouraged *multivocality*, individual expression of student ideas during classroom activities. They were given several opportunities to explain their notebook entries and science ideas.
**Researcher Positioning:** This research study offered students’ rich and interesting science investigations. Provided them with multiple opportunities to express and explain their science ideas in a safe and inviting setting. The science investigations were designed to promote student intellectual curiosity, challenge their own alternative conceptions while being immersed in science inquiry. The semiotic tools, probing questions and opportunities to explore a variety of phenomenon promoted a sense of wonderment and surprise. The objectives of this research study was to open up the classroom discourse in support of the student, provided teachers with opportunities to engage students in meaning making and provided tools that can further student curiosity throughout their lifespan. Since these are Urban/Suburban classroom settings *equity*, fairness and patience were practiced. As a *participant-observer* of African heritage every attempt was made not to show favoritism towards any one student.

**Triangulation:** Multiple forms of data (paper instruments, classroom recordings, notebook entries and interviews) were collected over multiple weeks. Researcher field notes were used to provide further context of the day-to-day experiences and multiple students were invited to talk throughout the study to ensure findings of the overall study represented the science classroom. A major part of this study was to connect student sign use in sense making around particular science topics. This semiotic approach ensured individual students had several opportunities to explore their science ideas.

**Outlier:** Classrooms were of mixed ability. Self-efficacy, interest and motivation all played a role in student performance. As data was collected and analyzed all attempts were made to identify student work that was outside the norm of current classroom expectations
with the goal of developing reasonable explanations as to why performance was greater or less than expected.

**Long-term Observation:** This research was interested in the process of learning—changes or evolution of student thinking over time. As well as the product of learning—documenting and analyzing student notebook work to help explain what students were thinking. Hence, the pilot and main research study were being conducted over many weeks to ensure students were comfortable with the presence of the researcher and students were provided with many opportunities to engage in semiotic discourse. This should have provided a truer picture of the students thinking.

**Code Checking:** Members of the research committee and expert peers helped establish inter-rater reliability in using the *Science Learning Trajectory Assessment Instrument* to analyze student self-explanations.

**Assumptions of the Study**

The teachers and students were not coerced in participating in the study. Every attempt was made to capture a full range of student voices. The qualitative data was collected, analyzed and presented with integrity and in accordance with proper research methodology outlined in this paper.
CHAPTER FOUR

RESULTS

The results will be organized into three sections. Section 1 contains descriptive statistics—demographic information on the participants, pre-post student scores on the nature of soil, student mean scores on four investigations tied to soil and water interactions, notebook page counts, and semiotic sign use in notebooks and during student pull-out interviews. Section 2 will provide three within-case analyses mapping specific student notebook entries with their interview responses on investigations 5, 6 and 7 on soil and water interactions.

Section 1: Descriptive Statistics

The Grade 3 science classroom was a near even split between male (48%) and female (52%) students. Fifteen (72%) of the 21 students agreed to participate in the study, of which 11 (52%) students agreed to be interviewed (Table 5).

Table 5: Demographic Information

<table>
<thead>
<tr>
<th>Number of Students</th>
<th>Male</th>
<th>Female</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Science classroom</td>
<td>10 (48%)</td>
<td>11 (52%)</td>
<td>21</td>
</tr>
<tr>
<td>Participants in the study</td>
<td>7 (47%)</td>
<td>8 (53%)</td>
<td>15</td>
</tr>
<tr>
<td>Students interviewed</td>
<td>5 (45%)</td>
<td>6 (55%)</td>
<td>11</td>
</tr>
</tbody>
</table>

Of the 21 students who participated in the study nine were Caucasian, 10 were African American and two were Asian. All the Caucasian students agreed to be interviewed, while one African American and one South Asian student agreed to be interviewed (Table 6).
Table 6: Number of Students by Ethnicity

<table>
<thead>
<tr>
<th>Participants</th>
<th>Caucasian</th>
<th>African American</th>
<th>Asian</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Science classroom</td>
<td>9</td>
<td>10</td>
<td>2</td>
<td>21</td>
</tr>
<tr>
<td>Participants in the study</td>
<td>9</td>
<td>5</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>Students Interviewed</td>
<td>9</td>
<td>1</td>
<td>1</td>
<td>11</td>
</tr>
</tbody>
</table>

A total of nine investigations were conducted as part of this study. Two investigations focused on the nature of soil (e.g., definitions of soil, properties of soil, and soil formation), while five investigations focused on soil and water interactions (e.g., soil smears, soil settling, soil water holding capacity, and soil erosion analogy). It was not the intention of this study to measure student overall performance but instead to map student semiotic discourse with their modeling inscriptions as a way to better understand their scientific explanations of soil science phenomena. The pre-post scores and mean scores were based on the Science Learning Trajectory Assessment Instrument, and used to identify patterns in student response on the nature of soil items, and soil and water interactions. Figure 11 & 12 are examples of student pre-post test scores on a scale of 1-5. A score of 2 (circled in red) indicates a novice explanation of soil while a score of 3 (circled in red) indicates an intermediate explanation of soil.
1. What is soil?
   - “Soil has rocks, worms, leaves, weeds, and old wood chips.”

2. How is soil formed (made)?
   - “Worms eat leaves and then digest the leaves, and then poop out dirt.”

3. What does soil do?
   - “It helps plants grow and gives homes to lots of creatures.”

Figure 11: Example Pre-assessment Score Based on the Science Learning Trajectory Assessment Instrument.

1. With the help of the following graphic define what is soil?
   “Soil is made of organic and inorganic matter such as leaves, branches, rocks, decomposed animals, roots, minerals and bacteria.”

2. How is soil formed?
   “Soil is formed when animals decompose or decay and weather makes them weather. Worms also add fertilizer to the soil. Bacteria and minerals also absorb into the soil.”

3. Why is soil important?
   “Without soil there would be no plants and trees. Plants and trees make oxygen and without oxygen there would be no people. Also plants and trees make food and without food there would be no people.”

Figure 12: Example Post-assessment Score Based on the Science Learning Trajectory Assessment Instrument.
Of the 15 students who completed the pre-post instrument, 2 (13%) students demonstrated no improvement in their score, 3 (20%) faired worse on the posttest than on their pretest, and 10 (66%) students showed improvement on their posttest score. Figure 13 illustrates the range of pre-post scores individual students received.

![Bar Chart](image.png)

Figure 13: Individual Pre-Post Student Scores on the Nature of Soil Items.

Table 7 provides raw scores for 11 students graphical and textual notebook entries (M₁, SD₁), and verbal and gestural responses (M₂, SD₂) on the same pages during their pull out interviews. The investigations labeled Notebook (NB) indicate pages created during the investigation, and (Quiz) for pages created during the summative assessment. The scores suggest students maintain alternative conceptions when explaining how and why soils settle differently in vials of water (Investigation 6) (M₁ = 1.54, SD₁ = .72) and (M₂ = 1.9, SD₂ =
.83), and when explaining the interaction of water and coffee grinds, erosion analogy (Investigation 13a) (M\(^1\) = 1.31, SD\(^1\) = .78) and (M\(^2\) = 1.54, SD\(^2\) = .93). Students maintained a novice level understanding on their verbal and gestural scores during the soil smears (Investigation 5a) (M\(^2\) = 2.09, SD\(^2\) = .94) and (Investigation 5b) (M\(^2\) = 2.45, SD\(^2\) = .52).

Lastly, students attained a novice level understanding of their graphical and textual inscriptions when explaining soil settling after 24 hours (Investigation 7b) (M\(^1\) = 2.45, SD\(^1\) = .56), compared to their verbal and gestural score where alternative conceptions persisted (M\(^2\) = 1.54, SD\(^2\) = .82).

Table 7: Mean Scores by Soil Investigation (Soil + Water Interactions)

<table>
<thead>
<tr>
<th>Investigation</th>
<th>M(^1)</th>
<th>SD(^1)</th>
<th>M(^2)</th>
<th>SD(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5a. Soil Smears (NB)</td>
<td>1.45</td>
<td>.78</td>
<td>2.09</td>
<td>.94</td>
</tr>
<tr>
<td>5b. Soil Smears (Quiz)</td>
<td>2.18</td>
<td>1.05</td>
<td>2.45</td>
<td>.52</td>
</tr>
<tr>
<td>6. Soil settling same day (NB)</td>
<td>1.54</td>
<td>.72</td>
<td>1.9</td>
<td>.83</td>
</tr>
<tr>
<td>7a. Soil settling after 24 hours (NB)</td>
<td>1.72</td>
<td>.93</td>
<td>1.36</td>
<td>.92</td>
</tr>
<tr>
<td>7b. Soil settling after 24 hours (Quiz)</td>
<td>2.45</td>
<td>.56</td>
<td>1.54</td>
<td>.82</td>
</tr>
<tr>
<td>13a. Soil erosion analogy (NB)</td>
<td>1.31</td>
<td>.78</td>
<td>1.54</td>
<td>.93</td>
</tr>
<tr>
<td>13b. Soil erosion analogy with scaffolds (NB)</td>
<td>1.45</td>
<td>.93</td>
<td>1.54</td>
<td>1.21</td>
</tr>
</tbody>
</table>

M\(^1\) = Graphic and textual mean score - Notebooks (NB) and Quiz
M\(^2\) = Verbal and gestural mean score - Pull out Interviews
Overall, 702 (8.5 x 11) notebook pages were photographed and catalogued, of which 366 were scored using the *Science Learning Trajectory Assessment Instrument*. Eighty notebook pages representing 11 students were recreated to support student self-explanations during their interviews. The 376 (54%) pages assessed covered 7 soil investigations related to the nature of soil, and soil and water interactions. The 80 (11%) notebook pages used during student self-explanations represented four investigations related to soil and water interactions.

Of the 366 notebook pages scored, 237 (65%) were created as iconic signs, while 80 (22%) incorporated symbolic signs. The majority of iconic signs consisted of models, diagrams and photographs of student work, while the symbolic signs included the graphic tools used to support student-constructed models. The high number of symbolic signs, used by students to document their observations and explanations, is of interest because it may suggest opportunities for abstract thinking. As well the use of these symbolic tools may present representations that are incorporating different views—macroscopic, microscopic and symbolic—of students understanding of PNM.

Overall, there were 213 individual gestures generated by students. Ninety (42%) of gestures were purely indexical (i.e., pointing to or circling) while the remainder, 123 (58%) were indexical + iconic, where a student incorporates a gesture to represent a phenomenological property or behavior (e.g., clasping) (Figure 14). There was one instance for molding, rubbing, and pinching, and 4-10 instances of either zigzagging, curling, spreading, overlapping, and tapping. Finally, there was more than a dozens instances of either sliding, clasping, fluttering, separating, and pulling-pushing gestures (Figure 15).
Table 8 provides descriptions of indexical, and indexical + iconic signs used by 11 students during their interviews. Many of the gestures were generated in combination with iconic and or symbolic inscriptions located in student notebooks.

Figure 14: Grouping of Gestures by Sign Type.
Figure 15: Individual Gesture Category Counts for Eleven Students Interviewed. The red indicates the two types of indexical gestures while the blue indicates the types of indexical + iconic gestures.

Table 8: Indexical Categories

<table>
<thead>
<tr>
<th>Code</th>
<th>Name</th>
<th>Description</th>
<th>Sign Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pointing to</td>
<td>Points to referent</td>
<td>I</td>
</tr>
<tr>
<td>2</td>
<td>Circling</td>
<td>Circular motion points to referent</td>
<td>I</td>
</tr>
<tr>
<td>3</td>
<td>Sliding</td>
<td>Sliding fingers or hand over pages</td>
<td>II</td>
</tr>
<tr>
<td>4</td>
<td>Verticaling</td>
<td>Ascending or descending motion of hands</td>
<td>II</td>
</tr>
<tr>
<td>5</td>
<td>Spreading</td>
<td>Spreading fingers apart</td>
<td>II</td>
</tr>
</tbody>
</table>
There was broad participation of students during the investigations (Table 6), with students being receptive to further explaining their inscriptions during the pull out interviews. One student had difficulty recalling two of the investigations during the interview process, feeling too much time had passed between the end of the unit and the pull out interviews. The spacing between the unit and interview was designed to minimize what Park and Light (2009) term as ritual knowledge, where students offer responses that are in keeping with their perception of teacher expectations. Secondly, an important aspect of meaning making in

<table>
<thead>
<tr>
<th>#</th>
<th>Movement</th>
<th>Description</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Tapping</td>
<td>Fingers tapping on the page</td>
<td>I</td>
</tr>
<tr>
<td>7</td>
<td>Clasping</td>
<td>Fingers touching and interlocking</td>
<td>I</td>
</tr>
<tr>
<td>8</td>
<td>Fluttering</td>
<td>Tips of fingers rubbing against one another</td>
<td>I</td>
</tr>
<tr>
<td>9</td>
<td>Overlapping</td>
<td>Horizontal movement of hands passing one another</td>
<td>I</td>
</tr>
<tr>
<td>10</td>
<td>Separating</td>
<td>Moving hands apart</td>
<td>I</td>
</tr>
<tr>
<td>11</td>
<td>Molding</td>
<td>Hollowed palms forming material</td>
<td>I</td>
</tr>
<tr>
<td>12</td>
<td>Pulling-Pushing</td>
<td>Draws hands towards and or away from body</td>
<td>I</td>
</tr>
<tr>
<td>13</td>
<td>Tilting</td>
<td>Rotating hand in place</td>
<td>I</td>
</tr>
<tr>
<td>14</td>
<td>Rubbing</td>
<td>Rubbing hands together</td>
<td>I</td>
</tr>
<tr>
<td>15</td>
<td>Pinching</td>
<td>Pinching thumb and first finger together</td>
<td>I</td>
</tr>
<tr>
<td>16</td>
<td>Zigzagging</td>
<td>Meandering hand motion</td>
<td>I</td>
</tr>
<tr>
<td>17</td>
<td>Curling</td>
<td>Curling fingers inwards towards palm</td>
<td>I</td>
</tr>
</tbody>
</table>

I = Indexical; II = Indexical + Iconic
semiotics is the initiation of sign use by the user during problem solving and reasoning activities. Too often students are directed to incorporate classroom practice that is not necessarily of their own volition. Spacing between classroom experience and the pull out interviews may have provided a better opportunity to observe student-driven critical reflection to further explanations (Lemke, 1998). This may reveal how and why students leverage modeling tools to manipulate their mental models.

The variation in student pretest scores on the nature of soil items (i.e., defining soil, explaining how soil is formed, and discussing why soil is important) (Figure 13) may be a result of novelty. Many students had not experienced soil science concepts prior to this unit. On the other hand, variation in student posttest scores (Figure 13) may be a result of individual development differences or the design of the study, since the guided inquiry driven investigations provided students with more latitude in thinking about a phenomenon. The aim was to help students identify their alternative conceptions than scaffold ways to help students interrogate and modify their conceptions over time (NRC, 2007). However, a four-week period may not have provided enough time for student scores to reflect changes in their science conceptions. Lee et al. (2004) and Jordan (2005) stress the importance of helping students distinguish between evidence and explanation. Helping students connect their perceptual observations, previous experience and cognitive tools may further shift their explanations towards more normative conceptions (Ford, 2005). It is possible the graphic scaffolds continued to challenge student thinking since it is asking them to distinguish phenomena at various scales (both macroscopic and microscopic) while using a variety of
sign types (Jaipal, 2009; Wiebe et al., 2009). Students require time and experience in developing their graphic literacy.

Student scores on the soil and water interactions (Table 7) covered their macroscopic observations of soil properties (e.g., color, texture, size, consistency). They could describe and summarize what happened but had difficulty explaining the material interactions using their graphic and textual inscriptions alone. Ainsworth, Nathan & Van Meter (2010) discuss the gap between perception-bound thinking and more abstract thinking, which for 3rd graders may be difficult to attain solely through inscriptions. There were a sizeable number of symbolic signs used over the course of the investigations but it remains unclear how these signs aid or detract from student science understanding. Are students adopting symbolic sign practices to highlight macroscopic observations or are symbolic signs used to further student abstraction? Verbal explanations may provide us with a better understanding of the impact of signs on student thinking. Similarly, is it possible their sign use was too literal, carrying properties and relations that are observed as opposed to being representative of the phenomenon (Cobley, 2010; Deloache et al., 1999).

One emergent theme that evolved during student verbal explanations was the use of gestures. The co-presence of gestures and verbal explanations (Kress et al., 2001) may provide some insight into how students need a variety of modes to fully articulate sign meaning. In some instances, gestures (Figure 14 & 15) (i.e., indexical signs) were used to point to a referent (notebook inscription) of the phenomenon during student explanation. While in many other instances gestures reflected a combination of referring to a phenomenon as well as describing properties or features of the phenomenon, what we are calling indexical
+ iconic signs. The use of indexical and indexical + iconic signs during student verbal explanation should not be undervalued, as it may play a vital role in supporting student reasoning (Semetsky, 2010; Ware, 2004).

**Section 2: Within-Case Analysis**

The within-case analysis will include the context of the investigation, description and summaries of student explanations, student artifacts and explanations, and analysis of student responses. The context for this section will apply to all three cases that follow, with each case representing three separate groupings (novice, novice-intermediate and intermediate-advanced) based on the *Science Learning Trajectory Assessment Instrument* used to score student notebook artifacts and verbal self-explanations.

**Context**

Students were given worksheets associated with each investigation. The classroom activities were designed to promote semiotic discourse across multiple modalities. The students’ prior knowledge was integrated into all the investigations. The instructor encouraged peer-to-peer and classroom discussion to further science understanding. The classroom was organized into small pods of 3 to 5 students per table (Figure 16) and resources from a variety of sources (e.g., Internet, video and stylized diagrams) were used to ensure a positive learning experience. The spacing between classroom investigation, summative assessment and individual interviews was approximately 5 days between the end of the soil unit and the assessment, and 10-14 days between the assessment and individual interviews.
Figure 16: Grade 3 Science Classroom Layout.

A summary of the investigation, concepts covered, and interactions for day 6, 7 and 8 were as follow.

- Day 6: *Investigation 5 - When soils get wet (mud smears).* This was a 35-minute classroom activity where students were involved in an expressed modeling phase. Students created a recipe for mud then made a smear. This was followed by individual sand, clay and humus smears. Throughout this investigation, students were given opportunities to predict and create smears and later during their summative assessment were asked to analyze photographs of smears created during their investigation. This exercise focused on differences in soil properties, how particles (grains of soil) are affected by water, and differences in the resulting smear. The majority of
students had never done a smear prior to this investigation—they needed practice in the mechanics of making soil smears, and were unsure of the ratio of water to soil components. This investigation provided another opportunity to leverage the Magnifier and Particle Tools to illustrate differences in smears based on soil properties.

• Day 7: Investigation 6 – How quickly do soils settle in water? This was a 35-minute activity where students were involved in an expressed modeling phase. Students created three separate soil vials (10-20 pinches), one for each sand, clay and humus, and then added water to each vial. For each soil component they documented similarities and differences in soil behavior at 0, 4, and 8 minutes in both textual and graphical modes. The Frames Tool was introduced to convey the importance of change over time. Several students found it difficult to write, draw and label their observations within a 35-minute investigation.

• Day 8: Investigation 7 – More settling after 24 hours. This was a 35-minute activity where students were involved in an expressed and public-consensus modeling phase. Students created representations of their soil vials the following day. This was followed by a class discussion on the differences in smears and student representations on the Smartboard™. Additional models of soil settling were placed on the board and the effect of buoyancy and gravity on the rate of soil settling was discussed.
Description, Evidence and Analysis

Case 1: Novice Explanations – Soil + Water Interactions

Investigation 5 - When Soils get Wet: Table 7 provides mean scores for this investigation across students’ graphical, textural, and verbal explanations. Individual student scores varied and clustered into three groupings, from novice to advanced, on the Science Learning Trajectory Assessment Instrument. The first case will represent N=6 students who held onto novice-level alternative conceptions during their explanations.

When students were asked to describe and explain differences in their soil smears, they created iconic representations of soil smear predictions reflecting a continuous view of the phenomenon. Perhaps because of this, students had difficulty relating the phenomenon to the process of smearing. Their textual predictions emphasized the readily accessible properties of soil (e.g., texture, color, grain size, structure and consistency). During verbal responses several students included personal experiences (playing at the beach) to describe the texture of wet sand.

Hannah’s smears were typical of the work of the novice students. Her iconic prediction represented a continuous view of soil, with her textual prediction focused on the properties of soil (the proximity of soil grains to one another). In her textual inscription Hannah captures the idea of soil particles but it is not reflected in her iconic drawing (Figure 17). Her verbal response includes an analogy when she compares her sand smear to Oreos, but overall remains fixated on the human-scale properties of soil (color and consistency).
• I smeared my soil really lightly. It spread apart when I spread it. I think the particles spread apart.

[Interviewer] …what was the difference between your prediction, what actually occurred and your findings?

[Hannah] Well I thought this (sand smear) would really get dark {Gestures: circling to sand smear} and really not spread out and clump {Gestures: clasping of hands, representing clumping} together. But apparently it just spread out more because of the fingerprints and all of the clay (sand) and because they're really big and so they can spread apart easily. Now the clay I predicted right because I thought it would stay together … and it would stick
together and get really small. And the [Gestures: circling to humus smear] humus, I thought it would all stick together ... and get really dark color but apparently it looked like Oreos and it got really light.

[Interviewer] How are they (sand, clay and humus) different?

[Hannah] This (sand) is the biggest and it has the lightest color. This (clay) is the smallest and it has a [Gestures: fluttering, representing size/property of soil] orange color. This (humus) is in the middle of sand and clay and it is the darkest one.

During the summative assessment students were given a photograph of the sand, humus and clay smears to analyze. They incorporated symbolic signs by drawing- over the photographs using the Magnifier and Particle Tool to illustrate differences in particles size and proximity of particles to one another. In several instances, students used small dots to represent a particle view of soil.

Hannah incorporates the graphic tools to represent the difference in proximity and grain size. Her representations within the magnifying tool remain iconic. In her textual response, Hannah remains focused on the properties of different soil types, specifically differences in particle size and their consistency when smeared (Figure 18). Hannah’s verbal explanation continues to capture the macroscopic view of the phenomenon, and expresses misconceptions surrounding the effect of air on particle size. While she talks about the “particulate nature” of soil, she is focused on the macroscopic characteristics of the smearing process, rather than what the smear reveals about the microscopic properties of soil. As the conversation persisted, she begins to lose her train of thought when comparing differences in soil smears.
Figure 18: Investigation 5 (Summative Assessment), Graphic and Textual Explanation of Soil Smears.

- (Soil Type 1) Well since clay is 100x smaller than sand. … it is more clumped together.
- (Soil Type 2) Humus is bigger than clay but smaller than sand so it is not clumped together as clay when it is dry and wet.
- (Soil Type 3) Sand…is the biggest and roughest of the clay and humus. It has the biggest particles (and) it won’t be as clumped together as the other (soil types).
When probed about how she incorporated the Magnifier Tool, Hannah replied:

[Hannah] Well the clay {Gestures: points to the clay smear} I think (it) kinda spread apart {Gestures: finger slides down the paper, illustrating a smearing action} because of the fingerprint, (it) kinda got spread apart … because of what the smear did to it.

[Interviewer] What did the smear do to the clay?

[Hannah] It spread it (clay) apart.

In this excerpt Hannah compares soil types.

[Hannah] …it has little particles {Gestures: circular motion} beside it and it got clumped together (humus). But this (sand) got more spread apart than the clay. And it had some air in it or little spaces in it, that's why it is not that dark as it supposed to be. But this (clay) uhm it's not that dark either because the clay absorbed the water…

When Hannah was probed further about differences between the soil components, she replied:

[Hannah] Well since clay is 100 times smaller than sand. I don't know let me just think.

[Hannah] Oh, this (clay) is smaller than this (sand) because there are little dots in between and air got in between them and the water absorbed this (sand). And the water really didn't absorb that much, and it (clay) still (was) a 100 times smaller and it spread apart.

Investigation 6 - How Quickly do Soils Settle: The representations of soil were primarily iconic in nature. There was one instance where a student’s predictions incorporated a particle view of soil combining the Particle Tool and dots to represent soil grains. Students’ textual descriptions included annotations and written explanations describing the different colors of soil, their texture, “humus was muddy”, and the sinking or floating of soil, “humus was found on top and on the bottom.” Student verbal explanations included many
macroscopic observations related to properties of soil such as “clay was sticking to the sides of vials.” Several students attributed sinking and floating to the amount of water soil absorbs (e.g., humus) or sinking as the result of air and water pushing on the soil particles.

Hannah’s graphical and textual observations emphasized macroscopic properties of soil (e.g., color) in the vials, how weight affects the sinking and floating of particles, and how soil dissolved in water. Her annotations provided macroscopic observations related to change in color and sand particles over time. Hannah’s verbal response merges general macroscopic observations (e.g., soil color) with explanations of why weight affects the floating or sinking of soil (e.g., sand) (Figure 19). During her verbal explanation Hannah proposes air is responsible for humus floating in the vial. In the last exchange Hannah takes an anthropocentric view of soil, suggesting soil particles can “insert” air into themselves.

Figure 19: Investigation 6, Graphical and Textual Explanation of Soil Settling.

- The sand is heavier than the water, (it is) moist (and a) bright color.
• The clay is heavier than the water, moist (and) darker.
• The humus is in the middle, heavy and lightweight, (it got) moist (and) got lighter.

When Hannah was asked to describe what happened in the vials, she states:

[Hannah] Well, for the sand it (got) really dark, well it had a light color and … the color changed in these settings (in the vials) but the sand just goes down to the bottom. And some of the humus stay(ed) at the top because humus has air stuck in it {Gestures: circular motion as she speaks about humus} and so it would go to the top. But since the grains (of sand) are so big, they can smush together and they don't really have any air so they all sink to the bottom.

When Hannah is asked to explain the relationship between humus and air, she states:

[Hannah] The humus … is really soft and it can put air in itself and the clay cannot. … Even though the sand is the biggest particle the humus got a little air in it because of the soft feeling of it and you can tell there is a little bit of air in every particle so it (humus) went up once (then) went (sunk) to the bottom.

Investigation 7- Soil Settling After 24 Hours: Students created iconic drawings (replicating the soil and vials) while representing soil as continuous. The students’ textual responses focused on smell, “sand smells like the ocean”, and soil location in the vial. One student made a causal link, suggesting the sinking and floating of humus is due to the amount of water retained and the weight of the material.

When reviewing the same question on their summative assessment students’ graphical representations included both iconic and symbolic aspects in their analysis. Students incorporated a draw-over technique, of the photographed vials, using the magnifier and particle tool. Textual explanations remained macroscopic and focused on properties such
as smell and location of grains within the vials. One student’s macroscopic observation included a rich understanding of soil and water interactions explaining how water separates sand particles and how clay breaks up into smaller and smaller pieces, highlighting a particulate view of soil.

Hannah’s graphical response utilizes the draw-over technique to explain the particle view of soil, providing a series of macroscopic observations related to soil consistency, the proximity of soil to one another, and tries to incorporate weight and density to explain why certain soil types sink. Her textual explanation remains fragmented while in her verbal response she continues to have difficulty explaining why humus contains air (Figure 20). She has elements of productive conceptions—the use of science concepts that can further her understanding of the phenomenon. For instance, she is fixated on air space being responsible for humus floating, when a discussion of density may have provided a better way of explaining sinking and floating of materials. However, she was not able to convey her ideas by incorporating the Magnifier Tool nor link how it might relate to settling. On the right hand side of the page Hannah revisits her explanation by including new graphical inscriptions. The incorporation of graphic edits during her verbal explanation was common for several students. As with other students, Hannah’s edits were done in parallel as she explained her ideas. This need to incorporate another modality may have helped further her explanation. This notion of graphic editing will be revisited in the discussion.
Figure 20: Investigation 7 (Summative Assessment), Student Graphical and Textual Explanation of Soil Settling After 24 Hours.

- (Sand) fell to the bottom...because of its density and weight.
- (Clay) The clay absorbs the water and it (loses) its color. It falls because of its density.
- (Humus) It also (loses) its color because humus absorbs the water. And some of it has density and some of it doesn’t.

When asked to explain how she used the magnifier to explain her drawing, Hannah stated:

[Hannah] I think I was trying to explain how they are different, how they are bigger and smaller, and how they can clump together...
Hannah remained well versed in describing the general properties of soil. She consistently created iconic representations with and without the modeling tools. Her soil representations reflect a continuous view (Johnson, 1998) of matter even though as she progressed through the unit she expressed soil material in terms of particles. It is unclear whether she understands particles and soil as separate and distinct entities (Johnson, 1998). Hannah understands that air and material saturation “absorption” play a role in sinking and floating of humus. Her textual response in Investigation 6 – Soil settling compares soil material as heavier or lighter, while in Investigation 7 – Soil settling after 24 hours, her textual response stated sand settles because of weight and density. Hannah’s verbal responses remain fragmented when discussing the science concepts of weight, gravity and air. Bucat and Mocerino (2009) suggest students have difficulty making sense of microscopic reality from macroscopic observations. Hannah is aware of a particle view of soil, an important milestone in understanding PNM (AAAS, 1993; Harrison & Treagust, 2002), adding bits and pieces of information, yet struggled to adequately explain the interactions of different materials (Andersson, 1990). With more experience and scaffolding, it is possible Hannah could develop a more robust view of soil and its interactions with other materials (Brooks, 2009).

Case 2: Novice-Intermediate Explanations – Soil + Water Interactions

The difference in this case (N=3) of students and case 1 was their consistent scores throughout the investigations. Their explanations across modalities were more explicit. They readily incorporated the modeling tools, were more descriptive in their textual explanations and a greater willingness to incorporate abstract concepts with their observations during their
verbal and gestural responses. In *Investigation 5* student predictions included iconic representation of smears with one instance where small dots were used to illustrate soil as particles. Their textual descriptions highlighted properties of soil (e.g., differences in color, shade and texture), using terms like rough, smooth and scratchy for humus, clay and sand respectively.

Students’ summative assessment utilized draw-overs to incorporate their modeling tools with the iconic photographs to illustrate soil at a particle view. Their graphic use was much more explicit in trying to reflect a particle view of soil. Even though 2 of the 3 students had some difficulty integrating the soil concepts there was every indication they were fluent in using the modeling tools for purposes of abstraction.

Dana combines iconic representations and the modeling tools to represent soil smears. She is aware of particles but continues to try and represent a macroscopic view of them. Dana’s textual response documents many of the same properties observed by the other students, and includes real-world examples, “humus looks like little peanuts”, when comparing the different soil types. In her verbal response, Dana’s observations remain at a macroscopic scale, focused on the size of soil grains and the color of the different smears (Figure 21).

In her summative assessment Dana draws-over the photographed smears using the modeling tools and alters the geometry of her soil particles to reflect differences in soil types. Dana’s textual response includes invisible properties (e.g., air) to explain some of the contents of humus, while her verbal response is focused on the macro-properties of soil (e.g., closeness and size of particles) (Figure 22).
• The sand look(s) like little balls with about two specs in it. Also there are some tiny little specs alone.

• The clay looks like raised up lines with ridges in them (that are) connected.

• The humus looks like little peanuts and little specs.

When Dana was asked to compare her prediction to her observation, she stated:

[Dana] Well, for the sand I thought I was pretty accurate except {Gestures: points to sand prediction} in here I made little grains (that were) close together {Gestures: spreading suggesting grains were not that close together}
[Interviewer] What did you notice after you did your smear?

[Student] Well after I did my smear … it wasn't all covered with the grains there were only some (areas covered with sand grains).

When Dana moves on to describe the clay smear, she states:

[Dana] Well (Gestures: points to clay) obviously it was lighter when I smeared it and it was actually a little darker then I had expect it (to be). (Gesture: points to the magnify tool and clay smear) It was one little clump there and there and then … pieces (Gestures: a circling motion with her left hand mimicking the act of smearing) were around it like here and they were connecting to the bigger clump (Figure 22).

Figure 22: Investigation 5 (Summative Assessment), Student Graphical and Textual Explanation.
• Clay has extremely small grains that are very smushed and clumped together, forming one big irregular grain.

• Humus has a mixture of irregular grains and circles, but they have air/gas in between them, and so they are pushed away from each other.

• Sand has very few particles/grains they are much bigger than you think and they have a very irregular shape.

[Interviewer] Can you describe your smears, in the context of how you used the magnifier?

[Dana] For the clay, we talked about how packed together and clumped the particles are and so in a smear they would just be so tight together that there (is) no space for any part of the white (the white of the paper) to show.

[Dana] for the humus… they are medium size particles so they were kinda separated but they weren't exactly tight and packed together like the humus. So you did have, you could see a little white in between the particles and stuff.

[Dana] For the sand well (you) could see a lot of white in between because the particles are really separated because they are huge.

For Investigation 6, students’ graphical inscriptions depicted iconic representations with a continuous view of soil. Their textual responses describe macroscopic observations, “…in the sand vial the water was clear”, “humus floats” and “clay sinks”. One student attributed the difference between the sand grains sinking and humus floating to differences in density. Students’ verbal response remains focused on both the geometry of various particles and how density of material affects the downward movement of particles.

Dana’s graphic representation combines many of the macroscopic observations described above but also labels many of her diagrams describing the size and closeness of particles (e.g., the degree of clumping). In both her textual and verbal responses Dana
confuses density (e.g., thinking material can receive a certain amount of density) and attributes the downward movement of water to a force pushing on soil particles. She is very detailed in documenting both her graphical and textual observations, but finds difficulty in piecing together a scientific view of why soil settles at the bottom of vials (Figure 23).

Figure 23: Investigation 6, Student Graphical and Textual Explanation.

- First sand grains were all scattered, then at 4 minutes it (sand) was pushed down mostly to the bottom. When 8 minutes came, there was very little on the side and some on the bottom.

- (Clay) First there were little bubbles on top of the water and some clumps at the bottom. At 4 minutes all the clay was then at the bottom (resting) on top of the (existing) clay grains. At 8 minutes the clumps and grains had sunk to the bottom.
• (Humus) At first it was floating real lightly above the water. Then at 4 minutes some (humus) started to sink but some stayed up. At 8 minutes I thought the humus stayed the same but it was packed down more.

When Dana was asked why humus floats, she stated:

[Dana] Well maybe it was on the top upper part {Gestures: overlapping the left hand over the right hand to demonstrate the top of the vial} and so the water didn't reach it and the humus grains got some density in it and they fell down, but maybe those {Gestures: points to humus} grains didn't go down yet because they were on the upper half and they didn't get touched by water (as) yet...

In Investigation 7, students’ graphical representations combined iconic and symbolic view of soil. Soil that settled near the bottom of vials was represented as continuous with small dots used to represent the floating soil. In one instance the Magnifier and Particle Tool were used to highlight a particle view of soil. Annotations were used to identify soil particles, while one student incorporated a vector symbol to emphasize soil descending in the vial. Their textual inscriptions focused on the macroscopic aspects of soil settling “the clay was sinking”, “the humus floating” or “it smells” while students’ verbal responses remained focused on macroscopic aspects of the phenomenon.

Students’ graphical representations during the summative assessment were iconic and symbolic, utilizing dots to represent soil particles or using the Particle Tool to represent a particulate view of soil. Humus that accumulated either at the top, middle or bottom of the vials were depicted as continuous with either dots or particle symbols used to represent the soil. Student textual observations were macroscopic, describing the sinking or floating of soil components, highlighting certain properties of soil (e.g., the changing color as a result of
interacting with water) or differences in grain size. One student described how density and air affect the sinking or floating of soil material of sand and humus respectively.

Dana’s graphical representation stands out for her multiple use of the Magnifier and Particle Tool emphasizing the dispersion and accumulation of soil components at specific locations in the vials. She incorporates a continuous view (e.g., lines) to distinguish the water from the soil particles and provides detailed labeling to discuss change in color and soil movement down the water column. Dana’s textual explanations remarks on the role of water in separating sand particles and how clay continues to break up into smaller and smaller pieces. Suggesting specific causal relations between sand and clay. Her verbal responses focus primarily on sinking and the causal connection between humus, air and floating behavior (Figure 24).
Figure 24: Investigation 7 (Summative Assessment), Student Graphical and Textual Explanation.

- The sand grains all got pushed to the bottom, but as they went down, they left color into the water.
- The clay mostly sank to the bottom, but some of it stayed in the middle, and very little at the top, so all the water is red/orange.
The humus grains were all scattered in the water. The humus is thick, so it (the water) absorbed into the humus that collected it, and filled (the) vial up with mostly water.

In this excerpt, Dana discusses the use of the graphic tools to explain soil settling.

[Dana] For the humus, it was like this picture (refers to original observation graphic of soil settling after 24 hours). I have a lot of magnifiers, ok. So well, actually it was in reverse order because most of the water was now getting pushed up there most of the grains were sinking down to the bottom because they had already absorbed a lot of the water and that density had pushed them down to the bottom.

Dana describes the clay and sand observations in the following statement.

[Dana] For the clay, it was like the humus but it was a little different. Like there was some clay clumps down there but the grains were still floating around and the ripples in the water were also made of … ripples in the water plus the grains made particles which were the ripples. For the sand it was just a lot of grains at the bottom like most of them were there and they were really separated but you can't really see it until you magnify it because they seem really small but they are really big, and clay particles seem big but they are small.

These students attained a novice-intermediate level of understanding about soil and water interactions while continuing to hold on to several alternative conceptions. Dana had difficulty integrating concepts of density with her verbal explanations. It is possible her concept of density was being confused with weight and or gravity. These were terms explored during the unit but obviously Dana still retained an incoherent view of these concepts. Additional probes and real-time scaffolding could have helped revise and clarify her explanation. Student observations of smears and soil settling remained focused on the properties of soil (e.g., color, texture, proximity of particles, and size). This is in keeping
with students’ general tendency to document macroscopic observations. Wiebe et al. (2009) discusses the difficulty students have in creating representations that reflect the intersection between the observable and invisible phenomenon. Louca (2011) and Braaten & Windschitl (2011) note the difficulty students have in explaining causal relationships. This is at the heart of semiotics, where students must find ways to integrate their observable frames with abstract tools in order to make sense of phenomenon (Cobley, 2010). Dana’s representations showed some growth in consistently using the modeling tools to reveal a particle view of soil (Figure 24). Yet she was compelled to represent particles with a specific geometry when describing the shapes of different soil components (Figure 22). The use of dots in some of her drawings may be a shorthand version for particles because dots are faster to create, or it may suggest she is still finding difficulty using the Particle Tool effectively. Her multiple use of the Magnifier Tool (Figure 24) and discourse on the use of the modeling may suggest a meta-awareness of leveraging these tools to better illustrate her observations. Schwarz & White (2005) discusses the importance of metamodelling to promote accuracy, clarifying and broadening student understanding. In Dana’s case, along with other students, this act may suggest the early beginnings and awareness of these modeling tools to further their observations.

Case 3: Intermediate to Advanced Explanation of Soil + Water Interactions

The difference between this case (N=2) of students and cases 1 & 2 was their consistent explanations carried fewer alternative conceptions. In Investigation 5, Julien created iconic representations of his soil smears. He did not incorporate the graphic tools directly but, none-the-less, attempted to capture the details of his prediction (Figure 25). His
textual responses incorporated annotations focused on properties (e.g., color, texture, shape and consistency). While his verbal explanations captured macroscopic aspects of soil he uses an example of sand at the beach to explain his prediction of wet sand.

On the summative assessment, the other student used a draw-over technique on the photographed smears, incorporating the Magnifier and Particle Tool. The students’ textual observations documented macroscopic observations (e.g., texture, color and consistency). Their verbal and textual responses were similar in describing the properties of soil.

Julien created iconic and symbolic representations on his summative assessment, leveraging the Magnifier and Particle Tool to discuss soil properties (e.g., size and consistency), the geometry of soil grains, and a particle view of soil. The draw-over on the photographed smears were done while explaining the concept of smears. Julien demonstrated a high degree of fluency with the modeling tools during his explanation (Figure 26).
• The sand is light (in color) and it isn’t rough anymore.

• The clay is lumpy and moist.

• The humus smears easily (when) wet or not. It is dark in color.

When asked to explain his prediction for sand and clay, Julien states:

[Julien] … First I thought of like when I was at the beach and how the wet sand {Gestures: curling with right hand to indicate wetness} is all mushy and stuff and stuck together {Gestures: clasping of hands to show how sand is mushy and stuck together}, so I wrote down what that was {Gestures: a circular motion to indicate his sand prediction} …
Figure 26: Investigation 5 (Summative Assessment), Student Graphical and Textual Explanations.

- (Clay) You might see large chunks and smaller pieces. The clay would have different locations.
- The humus would look like powder. You could tell that it could easily come off.
- The sand would look like tiny clumps spread across the paper. Sometimes, they looked like geometrical figures!

[Interviewer] How would you describe each one of these soil types using your magnifier tool?

[Julien] Well {Gestures: points to the clay smear} clay. So I just (showed) you what the smear might look like {begins to draw over
the clay smear) well the clay I would say it would … have smaller chunks with bigger pieces because it did have water in it, so there would be bigger pieces with smaller chunks around it, very close together though. If I zoomed then you would see the big chunks, it would have cracks in it, (the) smaller chunks would be this size but it does not make much difference, except (that) you would see even smaller particles.

[Julien] And then sand, they are more geometrical shape, but not exactly...

[Interviewer] What do you mean by geometrical?

[Julien] Like (you would see) faces, bases, angles and vertices, well like not exactly a cube … more like something like this (finishes his drawing). When you look at it {Gestures: pulling fingers close to his right eye to illustrate that it is hard to see with the naked eye} with the eye it is hard to see but there are little chunks pretty much all the same size but I think some are different colors. Some are completely transparent (and) some are have their own color.

[Interviewer] When you say transparent what do you mean?

[Student] They don't have a solid color so you can see through them even though it is a bit hard to tell because {Gestures: fluttering, moves right thumb and first finger close together near his eye to illustrate difficulty in seeing a transparent particle} you are looking at them with your naked eye.

In Investigation 6, the students’ graphic representations were iconic representing soil as dots. Their labeling supported their macroscopic view of soil specifically, the settling of soil and color of water. Julien’s prediction was textual while the other student created iconic representations combining a continuous and particle view of soil. He was able to accurately use concepts of dissolve and weight to explain soil-settling phenomenon. Julien’s verbal explanation covers both macroscopic observation and an understanding of the role of density in soil settling (Figure 27).
Figure 27: Investigation 6, Student Graphical and Textual Predictions Followed by one Explanation.

- (Prediction) The sand will clump together and sink to the bottom because it is heavy.
- (Prediction) The clay will moisten and quickly sink. It will turn (a) brighter red.
- (Prediction) The humus will dissolve and the water will turn black.
- (Explanation) (Sand) The murky orange water slowly lowered with clear water trailing behind.

[Interviewer] Can you explain what happened for each one of vials over the course of 8 minutes?

[Student] Well first of all I was surprised sand left orange water (researcher interjects with “how come at first?” I think it is just smaller particles {Gestures: fluttering, motioning fingers as particles floating in water} floating in the water but then a line of clear water started coming down the longer it sat still.
[Interviewer] Why was that happening?

[Julien] Because the particles were {Gestures: verticaling, pulling hands up to be level with his chest, clasping, interlocking fingers and moving his hands down towards the table illustrating particles sinking} sinking to the bottom and the water was settling.

[Julien] And the clay, immediately settled to the bottom and some stuck to the sides with water. But then some orange water came with a bit of clear water on top. {Gestures: sliding, moving his hand back and forth on the page over the clay image}.

In Investigation 7, Julien’s graphical representation was iconic, mixing a continuous and particle view of soil. The textual component covered macroscopic aspects of the phenomena (e.g., the color of water, size of particles, and texture of soil).

For the summative assessment both students provided iconic and symbolic representations of soil using the Magnifier and Particle Tool. Annotations were used to highlight the stratification observed in the sand, clay and humus vials. Their textual responses documented their macroscopic observations (e.g., color, size and consistency) without explaining why there were differences in soil settling (Figure 28).
Figure 28: Investigation 7 (Summative Assessment), Student Graphical and Textual Explanations.

- The sand sunk to the bottom leaving the water beige. It clumped together to make mushy substance.
- The clay immediately sunk to the bottom. It changes when it hits the water, it gets softer.
- At first the humus floated but after 24 hours most of it sunk. Some stuck to the sides. The water didn’t look real when it was black.
In this sequence Julien is explaining his representation on the summative assessment.

[Interview] How were you using the magnifier tool here?

[Julien] It looked exactly like, can I write on it, (adds particles to sand vial) it looked exactly like the normal sand (pointing to vials). But then (gestures: pointing to drawing) it still looked like sand (then) the water cleared (up) a bit. It was not nearly as murky but still a bit murky.

[Julien] The clay did have a few chunks (adds particles) because it was just the beginning (to have) even tinier particles around here (adds dots to his drawing)…

[Julien] I don't know why I put the chunks but...

[Interview] What do you think you were trying to say?

[Student] Because it (clay) would look exactly like humus and I didn't want that to happen.

With further probing, Julien states:

[Julien] So really the chunks shouldn't be there but there were tiny particles (adds particles to drawing below and clay) maybe a few smaller chunks but the chunks pretty much fell apart in the water. Then there was orange and yellow water near the top.

[Interviewer] So why did the chunks fall apart?

[Julien] I think the water finally got its way into the clay and it broke it up {gestures: pulling, brings hands together loosely opening then separating} from the inside. They became tinier particles. And then the humus sunk to the bottom (adds particles to the drawing below to illustrate humus was floating in the water) but it left a few, particles in the water and so it kept the water black. Pitch black like the color and then a little bit of humus still did float on the top.

In an earlier sequence Julien is asked to elaborate on the term density.

[Interviewer] Can you explain why some of these soil types sink to the bottom?

[Student] I think they are more dense because...
[Interviewer] What do you mean by dense?

[Student] Well like clay there is more (particles) packed inside the pieces and sand well I mean like they’re solid {Gestures: fluttering, pinching of thumb and first finger to illustrate sand as a solid} and they are not like hollow. I’m not saying that humus is hollow but it has little tiny holes inside it. {Gestures: zigzagging, motion with right hand in the shape of the letter Z to illustrate humus has holes in it}.

[Interviewer] What do you think those holes are?

[Student] Air holes.

Julien demonstrated fluency in sign use across modalities, demonstrating the ability to describe events at various scales. His responses were precise, he was comfortable using the modeling tools, and readily integrated the science concepts to explain his observations. His graphical representations covered macroscopic aspects of the phenomena but also demonstrated emergent causal understanding of soil settling in his verbal explanation. He not only explained what happened but described the process. Louca et al. (2011) and Braaten & Windschitl (2011) consider explanations that incorporate semi-causal relationships an important stage in modeling and conceptual growth. Julien’s gestures were a central modality during his verbal explanations. Demonstrating modal co-presence, where multiple modalities are leveraged during an explanation (Kress et al., 2001).

When Julien was discussing the graphic tools, he demonstrated sophistication in trying to explain both observable and invisible aspects soil. He was not wedded to all his textual responses and was willing to reconsider his answer (Figure 28). This was evident when he was trying to explain how sand grains were transparent and when discussing the formation of clay from smaller particles. He was also able to define and integrate terms like
dissolve, weight and density into his explanations. When given the opportunity, Julien added to his drawings in order to clarify and expand his explanation (Figure 24). Even though Julien was still incorporating iconic representations with the modeling tools he was developing a coherent view of soil and water interactions.
CHAPTER FIVE

DISCUSSION

Metamodeling Overview

A distinct theme emerged as a result of the cross-case analysis, metamodeling—students’ awareness, use and reference to modeling tools during their self-explanation. It includes the construction of models and awareness of modeling tools to elaborate on ideas, discern patterns, make revisions (graphic editing), and make predictions and inferences of phenomena (Schwarz et al., 2009). In the following discussion, the role of modeling tools and graphic editing will be highlighted to synthesize the results outlined in the previous chapter, revealing aspects of student reasoning.

The Role of Modeling Tools in Student Explanation

Students consciously made use of modeling tools in their notebook entries and explanations of their reasoning. In several instances, students’ explicit mention of the Magnifier Tool was used to show more detailed view of the properties of soil material such as the clumping, spacing/organization or comparisons between soil particles in the vials (Investigation 7). The Magnifier Tool was also used to stress that soil material (e.g., clay) was made up of many smaller particles of clay (Investigation 5). In several instances, students referred to the Magnifier Tool to highlight changes in the color of water as a result of dissolving soil particles (Investigation 7) (Figure 29). The magnifier tool appeared to engage students in more detailed discussion on interactions between soil and water, and prompted them to further edit their drawing to clarify what they were seeing. In the following
discourse, Carter is moving between macroscopic and microscopic views of soil to explain his observation, all the while using the Magnifier Tool.

When Carter was asked about the use of the magnifier tool, he states:

[Carter] Here in the clear, yellowish water (adds sand particles to the magnifier tool) there were very few small particles not a lot, not that you could see with the naked eye. But here in the clay you could see them a little bit better (adds clay particles to magnifier), the water had more color to it. And then down at the bottom (adds additional particles) there was a lot of clay. … the sand had a lot on the bottom so it just sunk to the bottom. The humus again like earlier there was … a lot of particles (adds particles to his humus drawing) in the water and a lot of particles in the magnifier and there was some stuck to the top … and even more at the bottom just like the rest of them (soil types).

Figure 29: Investigation 7 (Summative Assessment), Soil Settling 24 Hours Later
Students’ awareness of the modeling tools was not confined to the within-cases discussed above. On day 5 students investigated the making of coffee. During this 55-minute investigation students created a prediction, and documented their observations by creating personal models, which would later be used to assess their understanding. The instructor then provided scaffolds in the form of a blackline accompanied with the magnifier tool as a way of revisiting their personal models and increasing their understanding of the coffee making process. Students were also engaged in public-consensus modeling exercise where they shared their work on the Smartboard™.

The following figures represent the four stages of Investigation 13—textual prediction, expressed model (initial observation), a revisiting of their observation using a blackline modeling tool, and textual and verbal explanation of the phenomenon. The textual prediction focused on the interactions between coffee grinds and water (e.g., coffee dissolving in water resulting in a change in the color of water), and how some coffee grinds could not fit through the coffee filter. Several students captured something akin to the above in their prediction, but also tried to incorporate the concept of water as a force that could either push the coffee through the filter or, in one case, completely tear the filter apart, forcing the coffee grinds to fall through. Students had difficulty understanding the interactions between coffee and water (e.g., water as a force that causes materials to erode), or the form/function relationship between particle size and coffee filters. The following prediction exemplifies many of the macroscopic observations covered by students and the challenges in providing an explanation with their prediction (Figure 30)
• [Caroline] I think that when we pour the water into the coffee filter it (the coffee) will get so heavy that the water will push the coffee through the coffee filter and it will go through the funnel into the jar with the water. In the jar, the water will mix with the coffee and turn the water brown.

Students’ graphical representations were iconic, illustrating a combination of continuous and macroscopic view of the water and coffee interactions. A couple of students’ added color and labeling to their drawing while the majority simply represented the investigation set up. In the following example Gillian captures both the set up (left hand side) and result (right hand side) of making coffee. Her textual prediction emphasized the mixture of coffee grinds and water resulting in a color change (Figure 31)
When students were introduced to the blackline and *Magnifier Tool* their representations within the three magnifiers included iconic and symbolic representations of the phenomenon. The following exemplar captures the complexities students had in explaining the interaction between the coffee material and the process of making coffee. In the top *Magnifer* (Figure 32) Dana represented the coffee bean, small coffee grinds and air particles. In the middle magnifier she represented coffee beans being made of smaller particles of coffee. In the final *Magnifer*, she identifies a color change. Her explanation is incorporated in her labeling. In comparison with Figure 31, the graphic scaffolds isolated student work on the process of making coffee and not simply their macroscopic observations, which in Figure 31 were combined as one process. Supporting students’ causal understanding
of water and coffee may help further their understanding of the phenomenon. Alternative conceptions may persist but it provides an opportunity to support students in reconciling their ideas into normative scientific explanations.

In general students did not provide a separate textual explanation of how coffee was made, instead, relying on their previous prediction and graphic models to explain their ideas. Afterwards a public-consensus modeling exercise was conducted using the Smartboard™. A number of students used this opportunity to share aspects of their drawings throughout the three magnifiers. The interviewer initiated the exercise by adding representations of coffee grinds in the first Magnifer and a continuous view of coffee (colored lines) in the jar. Students then volunteered to enhance the drawing leveraging the Magnifier Tool. Students’
combined iconic and symbolic representations to develop a model of the coffee making process. There remained a tendency to include continuous view of the coffee mixture in the third magnifier. Near the end of the modeling exercise the instructor provided an explanation of how the coffee filter allows and limits the movement of coffee particles because of differences in size (Figure 33).

![Figure 33: Students Public-Consensus Modeling Cycle.](image)

The students’ verbal explanations during their pull-out interviews included descriptions of water pushing particles through the filter, how coffee particles make up coffee beans, and coffee as a mixture. Some students carried the conception of water absorbing coffee, while one student described water as picking up the coffee grinds, possibly alluding to the erosive force of water. Students continued to have some difficulty in combining their ideas into a cohesive scientific explanation. In the following example, the interviewer refers to the magnifier while asking the student to explain their observation. Carter explains how small bits of coffee passed through the filter even though this was not reflected in his revised drawing.
[Carter] Well there was the a little water with a few small particles in it and here there was still some soggy coffee {Gestures: points to the jar}.

[Interviewer] So would those be the same particles that you drew down here (in the jar) (as what) you drew up here (in the coffee filter).

[Carter] Ya, it's just that it, the water separated them (the coffee particles) so they are bigger up here (in the coffee filter) {Gestures: points to the coffee filter}.

Graphic Editing

Ideally, modeling should encourage students to refine their personal models through re-representations—the creation of a new representation based on personal reflection, new knowledge or understanding, or as a result of a new line of questioning. There were no instances of re-representation (through the creation of a new drawing) but instead several students *edited* their existing model during their verbal self-explanations as a way of clarifying, adding to, or reinforcing their understanding of a phenomenon (Case 1, Figure 20 & Case 3, Figure 26). The majority of students’ graphic editing during their pull out interviews of soil smears focused on representations related to particle size, consistency, clumping of clay particles, and organization. In the following example, Carter creates additional representations to enhance his soil smears. On the right hand-side of the page Carter’s first graphic edit represents sand particles as being spread apart, his middle drawing incorporates the *Magnifier Tool* to represent the density of clay, reflected in the addition of particles, and the third representation is of humus particles (Figure 34). There remains inconsistency in how he uses the magnifier tool to elaborate on his drawing.
When Carter was asked to consider similarities and differences between sand, clay and humus his graphic edits were accompanied with the following verbal response.

[Student] Well it was more, the sand can spread apart more easily, the clay can't really do it (spread apart) as good because it is clumped together, {Gestures: points to the clay smear} and it is not really in single particles, like I mean like the sand.

[Interview] What would you want to say about the humus?

[Student] The humus is not as clumped together as the clay, but it is still more clumped together than the sand, because there are little chunks of humus and not like single particles.

[Interview] Is there a drawing you could show me to help explain … the differences in the size of chunks?

[Student] Well, the sand would probably be like that (begins to draw sand particles on the right hand side of the page as closed dots) and then the clay would probably be like that (draws to large solid circles then uses the magnifier and particle tool to magnify the clay chunks) and this (are) little particles clumped together. And the humus would probably be like that, like smaller chunks.
but not as spread apart as sand (draws humus on the far right) sort of like that.

The final instance where graphic edits were prominent was during student self-explanation of their pre-assessment. Students received local garden soil. They explored the properties of soil, seeing live bugs (e.g., small spiders, worms and crickets) and a mixture of soil components. Students completed the pretest by answering three questions pertaining to the nature of soil and drawing their representation of soil. During their interview, students were asked to reflect on their experience and whether or not they wanted to add anything to their soil representation. The majority of students added labels and iconic representations of the contents of soil types (Figure 35). The stated curriculum did not provide students with an opportunity to revisit their representations. The graphic edit responses generated real-time verbal responses, suggesting students leveraged their representation to further reflect on their experience. As well, an important aspect of modeling was to understand when model construction becomes a learning strategy used by students without additional prompts or scaffolds. Meaning it becomes a learning necessity for student sense making. It was important to see whether or not students would incorporate the modeling tools or other representations as means of demonstrating deeper understanding.
Figure 35: Student Graphic Edits of Soil.

In one instance a student included the *Magnifier Tool* to create symbolic representations of different types of soil (Figure 36).
Figure 36: Student Graphic Edits of Soil Using the Magnifier Tool
CHAPTER SIX
CONCLUSION AND IMPLICATIONS

In answer to Research Question 1, graphically students used iconic signs to document their observations. Even though student notebook entries were found to incorporate the prescribed modeling tools there remained a tendency to document their observations in a macroparticulate view (Adadan, 2010; Johnson, 1998). They may understand soil to be made up of smaller particles but still see particles and soil material as separate entities. The more advanced students appear to understand soil to be made up of particles but they continued to leverage the modeling tools to represent the macro-properties of the phenomenon. They may also be trying to reconcile their prior experiences, their classroom observations, and explicit instruction about the invisible, which remains novel to many students. This is in keeping with the work by Talanquer (2009) who suggest students remain constrained by their concrete experiences. Ongoing instructional scaffolds that emphasize/contextualize the importance of abstract science concepts (e.g., gravity, friction & density) in explaining causal interactions is necessary. In general, there was little if any resistance to the adoption of the modeling tools to document their observations. The modeling tools provided a necessary bridge between the abstract science concepts and student observations.

Textual observations remained focused on observable aspects of the phenomenon. It was common for students to label their models to clarify “what” was being represented (e.g., clay, water and air). Several students did incorporate abstract science concepts (e.g., gravity, density and air) to explain differences in soil settling, but their explanations communicated no causality. Too often their textual inscriptions mirrored their iconic models. In some cases
students provided coherent sentences to explain what happened, their textual inscriptions adding to their observations. We feel the explicit use of text and graphics to support student thinking is an important aspect of meaning making. Only with ongoing, purposeful practice will students be able to merge their ideas into a coherent whole. Pedagogically, ongoing scaffolds are needed to help students articulate the interactions occurring between materials (Braaten & Windschitl, 2011; Louca et al., 2011).

Student verbal responses confirmed what was analyzed in their notebooks. Even though many verbal explanations focused on the macroscopic aspects of a phenomenon, their inscriptions provided another opportunity for students to critically reflect on the internal and external objects of their models (Justi et al., 2009). Their verbal explanations demonstrated the gap between describing the investigation (what happened) and the causal aspects. Many students would “drift”, lose their way as they began to explain “why” soil settles at different rates. They would confuse terms (e.g., weight = gravity), or have difficulty explaining the interaction between science entities and material (e.g., soil takes on density) when reasoning causally.

An emergent theme was the co-presence of gestures (Kress et al., 2001) during their verbal discourse. Students’ used indexical signs as a way of accessing the referent (the phenomenon under investigation). Students constructed (indexical + iconic) signs to support their explanation, help them remember a certain term, or as an alternative to using words to communicate their ideas (Kress et al., 2001). Some students appeared to use gestures as fluently as they could verbalize to explain their concepts. During the pull out interviews the interviewer was attentive to student gestures. Their gestures facilitated a more cooperative
conversation, inviting the interviewer into the student’s world. Gestures supported student verbal explanation of minute details that were often left out from their notebook inscriptions. It provided another opportunity to probe student thinking as they were searching for words or in support of their explanations. Gestures were used along with student notebooks and verbal explanations as a way to triangulate and assess their explanation in real-time. Elementary teachers should be made aware of the power of indexical signs to promote thinking, though it is still unclear how students can leverage indexical signs to communicate abstract science concepts.

Mental models are in a constant state of change (Johnson-Laird, 1983/2005). Student graphic edits and meta-awareness of the modeling tools, to amplify “zoom in” and dis-embed (Tsitsipis et al., 2010) a representation—soil as continuous to soil as made up of particles—were important aspects in student explanations. Students used these modeling tools as an extension and addition to their verbal explanations and graphical representations. Metamodelling supported student “moves” from simply documenting macro-scale observations to considering material interactions that occur at near-invisible or invisible scale. Smith et al. (2006) suggest metamodelling is an important modeling strategy for students who are describing and bridging observed events that require a microscopic view of properties to better explain a phenomenon. It is clear that without the modeling tools students would have been hard pressed to provide more detail about their observations at the particulate level.

Science notebooks provided a rich vehicle to gain a better understanding of students’ intentions. Their first person accounts in explaining what they observed and understand about
the particulate nature of soil helped bridge the researcher interpretations of student textual and graphical work. Even though the focus was on graphic models, students relied on their textual inscription to retrieve their understanding of the soil investigations. The notebook elicited “semiotic actions” during discourse in the form of gestures and metamodeling to extend their observations of the particulate nature of soil. The continued use of science notebooks provides students with a cognitive resource and, like other semiotic mediums, notebooks as a place-holder of student thinking, is a form of cognitive economy. Students can refer to details they may have difficulty retrieving from memory. Similarly, science notebooks are also an ideal space to mediate critical reflection.

In answer to Research Question 2, it is clear that students began to understand several basic tenets of PNM. Their representations reflected aspects of the proposed target models introduced with the Science Learning Trajectory Assessment Instrument. Even though students largely incorporated a macroparticulate view of soil in their representations, it still helped them realize that matter takes up space and has weight (NRC, 1996; Harrison & Treagust, 2002). Students expressed an awareness of different states of matter (AAAS, 1993), but it is unclear if they know matter can exist in several forms. Meaning whether or not ice, water and water vapor are made up of water particles. Students’ use of the term dissolve suggest they are beginning to understand that matter is conserved, that material is made up of small particles that are difficult to see with the naked eye (Johnson & Papageorgiou, 2010). We think students were shifting between Model X and A (Johnson, 1998); moving between a continuous view of particles and a macroparticulate view. In order to help students shift between macro and micro worlds continued instructional scaffolds that
link abstract concepts such as density, mass, weight and friction are needed to inform their observable frame.

To address Research Question 3, the semiotic analysis tool, *Science Learning Trajectory Assessment Instrument*, provided a window into student sign use that is often overlooked in the science education literature. The approach used in this research isolated sign use to a particular modality as well as provided an opportunity to analyze sign use in a more integrative manner across modalities. In middle elementary grades, students remain dependent on the referent to help describe and explain their science ideas. The research community must remain mindful of the semiotic resources used by students to represent science ideas. The ongoing challenge is to find ways to scaffold cognitive resources (modeling tools) to promote scientific reasoning. It is important to infuse students’ emerging graphic sign use with cognitions that are both embodied (indexical signs) and abstract (symbolic). Student gestures revealed a new category of signs, indexical + iconic signs. Explaining complex phenomena is often a multimodal semiotic endeavor.

**Implications**

This study found that incorporating model-based inquiry provided students access to a broader range of sign use for learning than they would normally experience. Connecting perception-bound observations and abstract science concepts should continue to be an important pedagogical goal in teaching science.

For teachers, we suggest more explicit curriculum decisions that contextualize the invisible concepts (e.g., gravity) within the overall curriculum is needed. In the current *Framework for K-12 Science Education* (NRC, 2011) cross cutting or big ideas in science are
being promoted as a way to improve teacher preparation. This will help teachers organize
their curriculum in a more coherent way. But there is still a need to support teachers in action
research or more formal classroom research settings to help change the classroom science
culture. Teachers must be supported in testing pedagogical ideas, given space to try new
instructional innovations to better understand the upper limits of student ability in areas of
abstraction.

For students, one alternative or addition to physical manipulatives is virtual
laboratory investigations. This would provide students with opportunities to more thoroughly
test models, a critical stage in meaning making. The opportunity to manipulate variables in a
virtual environment may provide students with immediate feedback that can refine their
explanations. The role of simulations would be to further their understanding of abstract
science concepts (e.g., density, buoyancy, friction, saturation and dissolving), which may
better support students during their investigations of the broader concepts in the physical
sciences. Students’ need less process oriented investigations and more purposeful
experiences that focus on interrogating abstract science ideas. The integration of common
and scientific language remains a challenge for many students. For science educators’
semiotic communication should be practiced across modalities in order to provide students
with the opportunities to make sense of the world around them.

**Limitations of the Study**

In this research it remained difficult to parse out student meaning making that was a
result of personal experience, collaborative effort, or some other intangible element. Also the
procedures were not standardized across the two cohorts, differences in age and teacher
comfort with the MBI approach altered the researchers instructional practice (e.g., amount of co-teaching required). There were data reduction difficulties with regards to the large number of interviews across a 9-week period, which may have affected how well data was consolidated to create a complete picture of student sense making. Classroom size limits to what extent the student experience is representative of larger classroom science experiences. This study did not utilize a control group to gage the differences in student explanations as a result of MBI instruction, as the purpose of this work was to extend research based on a previous research by Wiebe et al. (2009) where student explanations were not readily available. Interviewing students after several weeks may have put at risk their ability to recall the specifics of an experiment. However, it was necessary to have a gap between the science investigations and interviews in order to assess student sense making beyond the influences of real time classroom work. The researcher was compelled to include personal judgment as a criteria when choosing individuals to interview because they may not have been given enough time to acclimatize themselves to my participation in the classroom, they may not have liked me, or they may simply be stating what they think I want to hear. Literal-meaning semiotic analysis, meaning communicated across modes of expression, and short strings of words may not account for a full understanding of student thinking. Similarly, excluded hidden curriculum along lines of race, gender, ethnicity and language may have played a role in limiting the range of student responses. Finally, the cameraperson’s point of view during classroom investigations and pull out interviews may have generated a biased perspective (Erickson, 2006).
Future Work

A primary goal will be to refine the development and implementation of a *Science Learning Trajectory Assessment Instrument* to include student gestures more fully. In parallel, future work will be to develop science a learning trajectory that integrates elementary science units with national frameworks. This will help create age appropriate learning environments that combine physical and virtual manipulatives where students can build, test and revise models. Similarly, work to modify the MBI framework to research a blend of engineering and science education in elementary and middle school will help address elements of the new science education standards framework that calls for integrating elements of engineering thinking and design (NRC, 2011).
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APPENDIX A

MODELING DEFINITIONS

A list of modeling definitions used in STEM related disciplines.
Appendix A

<table>
<thead>
<tr>
<th>Type</th>
<th>Definition</th>
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<tbody>
<tr>
<td>Hypo-icon</td>
<td>A pre-icon considered an image but with no available information that will render it rationally understandable.</td>
</tr>
<tr>
<td>Sketch</td>
<td>A proto diagram a visual representation of a thought or idea in 2-dimensions or 3-dimensions, and often accompanied with annotations. (Lau et al., 2009; Stjernfelt, 2007).</td>
</tr>
<tr>
<td>Models</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Causal: represent cause and effect</td>
</tr>
<tr>
<td></td>
<td>• Computer-based: mathematically based constructs (e.g., applets or simulations) (Gilbert &amp; Watt-Ireton, 2003)</td>
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<td></td>
<td>• Conceptual: formalized mental model (Gilbert &amp; Watt-Ireton, 2003)</td>
</tr>
<tr>
<td></td>
<td>• Diagrammatic: contains relationships between multiple variables (e.g., systems diagrams, flow charts, blueprints, concept maps, topographical maps, 2-dimensional, 3-dimensional charts, graphs) where the words and objects represent relationships between objects rather than the scene directly (Gilbert &amp; Watt-Ireton, 2003; Bertin, 1983)</td>
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<tr>
<td></td>
<td>• Expressed: externalized representation of a mental model constructed from a variety of resources-signs and mediums (Gilbert &amp; Watt-Ireton, 2003)</td>
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<td></td>
<td>• Emergent: where relations between objects produce emergent behaviors that are not apparent in the description of either the object or the relation (Lehrer, 2006)</td>
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<td>• Expedient: simulate the behavior of the physical phenomenon without providing any access to the mechanism underlying that behavior (Louca et. al., 2011)</td>
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<tr>
<td></td>
<td>• Mathematical: based on quantitative values and relationships which cannot be validated by observation, and where the formulas and equations have propositional meaning (Gilbert &amp; Watt-Ireton, 2003)</td>
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<td></td>
<td>• Mental: personal perceptions of the external world, influenced by one’s memories</td>
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<td></td>
<td>• Perceptual: represent different parts of the model and their static depiction of the phenomenon</td>
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<td></td>
<td>• Process: are represented in the form of a conditional rules (Louca et. al., 2011)</td>
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<td></td>
<td>• Personal: student work used by the teacher to assess and evaluate the strength of their explanation or argument</td>
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<td>• Physical: a material model that is analogous to its target model but may or may not represent certain functional relationships to the target (Gilbert &amp; Watt-Ireton, 2003)</td>
</tr>
<tr>
<td></td>
<td>• Public/Consensus: are amendments to existing models through</td>
</tr>
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</table>
group discourse and critic

- **Simulation**: provide representation of the underlying mechanism that users can explore or alter (Louca et. al., 2011)
- **Target**: reflect consensus from the larger scientific community
- **Theoretical/Functional/Explanatory**: representations of the mechanism underlying the phenomenon (Louca et. al, 2011; Gilbert & Watt-Ireton, 2003)
- **Syntactic**: summarize the essential functioning of a system, typically bear little resemblance to the system being modeled and where understanding is derived from relational mapping (Lehrer, 2006)
APPENDIX B

TEACHER SOLICITATION LETTER

A solicitation letter sent to teachers to invite them to participate in the study
Appendix B

MONTH-DAY-YEAR

Researcher Contact Information

School Information

Dear: [Teacher]

Subject: New Research Interest

First on behalf of the GEES team I’d like to thank you for your ongoing participation and interest in our Graphic Enhanced Elementary Science (GEES) project. Over the past two years we have learned a great deal concerning the elementary science classroom, student learning and the ongoing challenges teachers face daily. The opportunity to engage directly with students, observe and videotape your classrooms during science instruction, and analyze student notebooks has raised some new questions.

Specifically, ongoing educational innovation is needed to support teachers in the integration of inquiry-based science and engineering design in the elementary grades. We understand that graphics and other modes of reasoning are central to student learning. A new area of interest is how to integrate big ideas in science and graphic-based modeling to enhance student scientific and engineering reasoning. In particular, we are interested in opportunities to integrate the particulate nature of matter, a central idea in science with broad explanatory power, into the existing kit-based science curriculum (e.g., Changes). We are committed to supporting Wake County schools and NCDPI’s standard course of study guidelines for elementary science education.

We think the use of student generated representations with our graphic tools and newly devised instructional innovations tailored to integrating matter-theory with the science and engineering concepts found in the kits could enhance student learning, and assist teachers in streamlining their science content requirements without compromising student success. Data collection would include student notebooks, classroom innovations (teaching experiments), and a series of 1:1 student interviews to map changes in student learning over time. In return I would be available as a science resource for planning and classroom support during instruction.

Once again I sincerely appreciate your time and look forward to discussing this further.

Sincerely,

Researcher Contact Information
APPENDIX C

TEACHER PRE-POST INTERVIEW PROTOCOL

Open-ended teacher interview protocol exploring their understanding of Foundational Images
Appendix C

Pre

What is your impression of the following graphics?

Do you associate any meaning (conceptual) or otherwise with these graphics?
   Do you have an example?

Do you think they should be modified in any way?

When is the most appropriate time to introduce these graphics?

What do you think of having a graphic wall or poster?

I’d like to get students early impressions of these graphics.
   As you introduce them.
   I’ll interview them when they are using them.
   During a point of reflection
I may videotape you when you are introducing a specific graphic. Is this ok?

Post

How have the students responded to the use of these graphics?
APPENDIX D

TEACHER PROFESSIONAL DEVELOPMENT PRESENTATION

PowerPoint presentation delivered to teachers who signed up to participate in the study
Appendix D

Modeling Terms in Context

- Mental model: Student ideas, mini-theories and conceptions, internal to the student’s mind
- Expressed (public) model: Information the student communicates using a variety of modes-verbal, written, graphical, gestural
- Consensus model: An expressed model that has been subject to peer critic, tested and agreed upon by the community of learners
- Target (Conjectural) model: the desired knowledge state of the scientific community. It may take several iterations/years for the community of learners to reach a robust scientific explanation
Models of matter

- **Model X**: Particles are in contact with each other substance. Particle ideas have no meaning beyond the macroscopic level.
- **Model A**: Particles are drawn, but the substance is said to be between particles. The particles are additional to the substance.
- **Model B**: Particles are the substance but with macroscopic properties. Particles are drawn and said to be the substance. There is nothing (empty space) between the particles. Individual particles are seen as the same quality as the macroscopic sample.
- **Model C**: Particles are the substance and the properties of the state are collective.

Matter and Landforms

- Erosion: Weathering of materials over time
- Sedimentation: Eroded material that has settled
- Physical Weathering: The disintegration of rocks into smaller pieces (particles)
- Chemical Weathering: The chemical breakdown of minerals dissolved in water, the replacement of ions with weaker hydrogen ions, and the interaction of oxygen with metals
- Biological Weathering: Organisms that break down rocks and minerals
- Soil: A mixture or weathered rock, air, water, and organic material
Matter and Soils

- Soil: a mixture or weathered rock, air, water, and organic material
- Weathering
  - Physical: the disintegration of rocks into smaller pieces (particles)
  - Chemical: the chemical breakdown of minerals dissolved in water, the replacement of ions with weaker hydrogen ions, and the interaction of oxygen with metals
  - Biological: organisms that break down rocks and minerals
- Roots create CO₂ (Gas exchange)
- Movement of particles between Horizons
- Compost: Water; CO₂; Heat; microorganisms; O₂; organic matter; minerals

Science Concepts

- Learning about Landforms infused with matter-theory requires knowledge of the following science concepts:
  - Gravity: a force of attraction by which terrestrial bodies tend to fall towards the center of the earth
  - Slope: a change in elevation
  - Saturation: the maximum quantity of water air can hold at any given temperature or pressure
  - Cohesion: the surface tension created by a small amount of water holds sand grains together
  - Friction: a force that results from relative motion between objects
  - Mass: the amount of matter an object has
  - Volume: the size of a body in three dimensional space
  - Force: a push or pull
  - Pressure: the force acting on a surface area
Student Outcomes

- Investigate water flow over earth materials in a stream table
- Observe the process of erosion, deposition, and stream flow
- Investigate how slope affects erosion and deposition
- Model and explain the process of landform creation.
- Integrate how particle shape, size, and material properties explain the processes and landform creation
- Build explanations by observing, communicating, comparing, organizing, and relating ideas
APPENDIX E

PARENT/GUARDIAN LETTER AND STUDENT/TEACHER CONSENT FORMS

Introductory letter sent to parents introducing the researcher, why the research is being conducted and asking them to complete the consent form allowing their offspring the chance to participate in the research study.
Appendix E

MONTH-DAY-YEAR

Contact Information

School Name

Dear: Parent/Guardian

Research Topic: Elementary Science Education

I am a graduate student in science education at North Carolina State University. Over the last couple of years I have been working with elementary science teachers on ways to use graphic tools in elementary science instruction.

This year I will be working directly with [teacher] on some new instructional tools. I would like the opportunity to talk with students individually and in small groups while [teacher] class is engaged in science instruction. Our conversations will be about the science activity they are working on and about what they are learning in science in general. I also believe our conversations will be beneficial to their learning.

Enclosed is an Informed Consent Form for Research outlining my research and asking you and your child’s participation. At times I will be recording student responses and taking photographs of their science notebooks as part of my research. Your child will not be identified in these recordings.

If you agree to participate, please read then you and your child sign, date and return the attached consent form. If you have any questions please contact me or [Teacher]

Sincerely,

Contact Information
Student Consent Form

North Carolina State University
INFORMED CONSENT FORM for RESEARCH – Student

Title of Study: Modeling, Matter and Scientific Discourse in Elementary Science Education

Principal Investigator: [Name] Faculty Sponsor (if applicable): [Name]

We are asking you to participate in a research study. Your participation in the study is voluntary. You have the right to be a part of this study, to choose not to participate or to stop participating at any time without penalty. The purpose of research studies is to gain a better understanding of a certain topic or issue. Research studies also may pose risks to those that participate. In this consent form you will find specific details about the research in which you are being asked to participate. If you do not understand something in this form it is your right to ask the researcher for clarification or more information. A copy of this consent form will be provided to you. If at any time you have questions about your participation, do not hesitate to contact the researcher(s) named above.

What is the purpose of the study?
The purpose of this study is to gain a better understanding of how students represent and make sense of specific science concepts traditionally taught during their standard science unit.

What will happen if you participate in the study?
If you agree to participate in this study you will be interviewed a set number of times over the course of a science unit. Some interviews will be one-on-one while other interviews will be conducted in small group and whole-class setting. We are interested in how you think and reason about science concepts described in the standard science curriculum. To gain a more holistic view of your scientific ideas, your written work, drawings and verbal responses will be collected. Your name will not be attached to the interview or copies of your classroom work in any way shape of form. If you agree to participate you are agreeing to be included in the video recording, and allowing us to photograph your notebook pages. Only project staff will view entire video tape recordings and notebook pages. Video clips and notebook pages might be presented at educational conferences.

RISKS
There are no known risks or discomforts associated with this study.

BENEFITS
By engaging students in talking, writing and drawing out their ideas in science, we can improve student scientific thinking, develop a better understanding of student scientific
learning and provide educational experiences that are both meaningful and relevant to students.

CONFIDENTIALITY
The information in the study records will be kept strictly confidential. Data will be stored securely in a password-protected server that is accessible only by the principal investigator and the faculty sponsor. All hard copies will be kept in a locked cabinet.

Original video recordings and notebook photographs will be kept for up to five years in order for researchers to continue to have access to the original source while data is being analyzed and confirmed. You will NOT be asked to write your name on any study materials so that no one can match your identity to the answers that you provide. No reference will be made to specific individuals in oral or written reports, which could link you to the study.

COMPENSATION (if applicable)
For participating in this study you will not receive any compensation.

EMERGENCY MEDICAL TREATMENT (if applicable)
Not applicable

What if you have questions about your rights as a research participant?
If you feel you have not been treated according to the descriptions in this form, or your rights as a participant in research have been violated during the course of this project, you may contact [name], Regulatory Compliance Administrator, [Address/Phone Number].

PARTICIPATION
Your participation in this study is voluntary; you may decline to participate without penalty. If you decide to participate, you may withdraw from the study at any time without penalty and without loss of benefits to which you are otherwise entitled. If you withdraw from the study before data collection is completed your data will be returned to you or destroyed at your request.

CONSENT TO PARTICIPATE

_____ I give permission to North Carolina State University to make and to use audio and video recordings of my child during his/her participation in normal classroom activities. These recordings will be used for conference presentations only. I understand that I will not be compensated for any recordings that may be used in this capacity.

_____ I give permission for photographs of my child to be used for conference presentations
I give my permission for my child’s classroom work, produced as part of their classroom activity, to be used for conference presentations only. I understand that no monetary compensation will be given for the use of the materials.

“I have read and understand the above information. I have received a copy of this form. I agree to participate in this study with the understanding that I may withdraw at any time.”

Subject's signature: __________________________ Date ________

Parent or Guardian’s signature: ______________________ Date ________

Investigator's signature: __________________________ Date ________

Principal Investigator contact information:

Keep a copy for your records and return the original signed form to the research team.
Teacher Consent Form  
North Carolina State University  
INFORMED CONSENT FORM for RESEARCH – Teacher

Title of Study: Modeling, Matter and Scientific Discourse in Elementary Science Education

Principal Investigator: [Name]  
Faculty Sponsor (if applicable): [Name]

We are asking you to participate in a research study. Your participation in the study is voluntary. You have the right to be a part of this study, to choose not to participate or to stop participating at any time without penalty. You are not guaranteed any personal benefits from being in a study. The purpose of research studies is to gain a better understanding of a certain topic or issue. Research studies also may pose risks to those that participate. In this consent form you will find specific details about the research in which you are being asked to participate. If you do not understand something in this form it is your right to ask the researcher for clarification or more information. A copy of this consent form will be provided to you. If at any time you have questions about your participation, do not hesitate to contact the researcher(s) named above.

What is the purpose of the study?
The purpose of this study is to better understand the instructional strategies needed to support student sense making in science in written, verbal, and graphic form.

What will happen if you participate in the study?
If you agree to participate in this study you will allow the principal investigator to observe your science classroom and participate as a teaching assistant during science experiments. During classroom time, the principal investigator is requesting permission to videotape. Video recordings may be made before, during or after science experiments in order to document student scientific thinking and reasoning. Only the principal investigator and faculty advisor will view entire videotapes. Video clips of classroom practices may be used during educational conference presentations.

RISKS
There are no known risks or discomforts associated with this study.

BENEFITS
By assessing teacher instructional strategies that engage students in opportunities to talk, write and draw their ideas in science, we can improve student scientific thinking and gain a better understanding of student scientific learning.

CONFIDENTIALITY
The information in the study records will be kept strictly confidential. Data will be stored securely in a password-protected server that is accessible only by the principal investigator.
and the faculty sponsor. Your name will not be shared with anyone else, including other staff or administrators in your school district. Original video recordings will be kept for up to five years in order for researchers to continue to have access to the original source while data is being analyzed and confirmed. You will NOT be asked to write your name on any study materials. No reference will be made to specific individuals in oral or written reports, which could link you to the study. When we report on data associated with this project in papers and presentations, results will be reported in aggregate or, if a quote from you is used, you will be referred to by an acronym (e.g., “Teacher A”). However, if you give permission to be videotaped, your identity may be known by those who view these tapes.

COMPENSATION (if applicable)
For participating in this study you will not receive any compensation.

EMERGENCY MEDICAL TREATMENT (if applicable)
Not applicable

What if you have questions about your rights as a research participant?
If you feel you have not been treated according to the descriptions in this form, or your rights as a participant in research have been violated during the course of this project, you may contact [Name], Regulatory Compliance Administrator, [Address/Phone Number]

PARTICIPATION
Your participation in this study is voluntary; you may decline to participate without penalty. If you decide to participate, you may withdraw from the study at any time without penalty and without loss of benefits to which you are otherwise entitled. If you withdraw from the study before data collection is completed your data will be returned to you or destroyed at your request.

CONSENT TO PARTICIPATE

Please initial by the statements that apply to you.

_____ I give permission to North Carolina State University to make and to use audio and video recordings of me during my participation in my normal classroom teaching. These recordings will be used for conference presentations only. I understand that I will not be compensated for any recordings that may be used in this capacity.

_____ I give permission for my photographs to be used without compensation for conference presentations only.
I give my permission for my example work produced as part of this project to be used for conference presentations only. I understand that no monetary compensation will be given for the use of the materials.

“I have read and understand the above information. I have received a copy of this form. I agree to participate in this study with the understanding that I may withdraw at any time.”

Subject's signature___________________________________ Date _____________

Investigator's signature________________________________ Date _____________

Principal Investigator contact information:

Keep a copy for your records and return the original signed form to the research team.
APPENDIX F

GRADE 5 INSTRUCTIONAL SEQUENCE
### Appendix F

<table>
<thead>
<tr>
<th>Days</th>
<th>Title</th>
<th>Description</th>
<th>Roles</th>
<th>Teacher</th>
<th>Researcher</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Introduction to stream tables</td>
<td>Students build a model stream table using the kit-based materials</td>
<td></td>
<td>X</td>
<td>O</td>
</tr>
<tr>
<td>2</td>
<td>Erosion</td>
<td>Students build a stream table changing the volume of water applied to the plateau and explore the various landforms created</td>
<td></td>
<td>X</td>
<td>O-I</td>
</tr>
<tr>
<td>2</td>
<td>Deposition</td>
<td>Students build a stream table combining die and water to explore how water influences landform creation and sedimentation</td>
<td>O</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>1</td>
<td>Slope</td>
<td>Students build a stream table changing the elevation to explore changes in the rate of erosion and depositions</td>
<td></td>
<td>X</td>
<td>O-I</td>
</tr>
<tr>
<td>1</td>
<td>Glaciers</td>
<td>Students explore physical weathering through glaciers using stop motion photography and 3D models built of gelatin.</td>
<td>O</td>
<td></td>
<td>O-I</td>
</tr>
<tr>
<td>1</td>
<td>Design your own investigation (Dams)</td>
<td>Students design their own experiment</td>
<td></td>
<td>X</td>
<td>O-I</td>
</tr>
</tbody>
</table>

X = Instruction, O = Observation, I = Interview, N = Not in attendance
APPENDIX G

GRADE 3 INSTRUCTIONAL SEQUENCE
<table>
<thead>
<tr>
<th>Days</th>
<th>Title</th>
<th>Description</th>
<th>Roles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pretest and Museum Day</td>
<td>Students explore garden soil, generate observations and complete a pretest</td>
<td>O</td>
</tr>
<tr>
<td>2</td>
<td>Introducing Sand, Clay Humus and man made materials</td>
<td>Students create observations of soil properties and components, and are introduced to modeling Tools</td>
<td>O</td>
</tr>
<tr>
<td>2</td>
<td>Making Coffee</td>
<td>Students make coffee to explore aspects of erosion and deposition</td>
<td>O</td>
</tr>
<tr>
<td>1</td>
<td>Mud Smears</td>
<td>Students observe what happens when soils and coffee interact with water.</td>
<td>O</td>
</tr>
<tr>
<td>1</td>
<td>Soil Smears</td>
<td>Students create soil smears and generate observations using modeling tools</td>
<td>O</td>
</tr>
<tr>
<td>1</td>
<td>Can soil hold water</td>
<td>Students place individual soil types (Sand, Clay and Humus) in a filter paper+funnel and observe what happens when water is poured over each</td>
<td>O</td>
</tr>
<tr>
<td>2</td>
<td>How quickly does soil settle in water?</td>
<td>Students place different soil components into three separate test tubes and observe the settling rate of each. The Frames Tool incorporates a Blackline to support student documentation and their observations.</td>
<td>O</td>
</tr>
<tr>
<td>5</td>
<td>What is your mystery mixture</td>
<td>Students conduct a guided investigation to identify different mixtures (i.e. cement, soil and facial clay)</td>
<td>O</td>
</tr>
<tr>
<td>2</td>
<td>Post Test</td>
<td>Students complete a posttest</td>
<td>O</td>
</tr>
</tbody>
</table>

X= Instruction, O= Observation, I= Interview, N= Not in attendance
APPENDIX H

GRADE 5 IN-CLASSROOM QUESTION GUIDE
Appendix H

1. Student stream table experiments will be documented in their notebook

2. Students will be encouraged to share their observations with the researcher

3. Students will be encouraged to share findings
   a. Probe students to discuss macroscopic observations to microscopic properties
   b. Probe students to distinguish material composition on the stream table plateau versus the sediment involved in shaping landforms
APPENDIX I

GRADE 5 IN-CLASSROOM INSTRUCTION PROTOCOL AND QUESTION GUIDE

Grade 5 Mini-Experiment
Appendix I

Coffee filter as an analogy for Erosion and Groundwater

1. Students divide notebook pages into 2 parts
   a. ½ the page used to predict what will happen when warm water interacts with coffee grinds [It’s important they have a chance to complete their prediction
   b. Second half describing in words and pictures what happened
      i. Probe students to discuss differences in particle size
      ii. Probe students to discuss differences in water color
      iii. Probe students to think about the impact of temperature
      iv. Encourage students to revise their drawing
      v. Probe students to compare their macroscopic observations to the microscopic phenomena (what is in the fluid)
      vi. Probe students to explain their drawing in detail
   c. Suggest summary comments: coffee beans are made of a variety of things. Hark back to food chemistry (lipids, carbohydrates, protein, minerals)
      i. What’s in the water?
   d. Compare to weathering, erosion or deposition. This analogy may come up again during subsequent stream table experiments

Materials
  • Warm water
  • 7 beakers
  • 7 funnels
  • 7 coffee filters
  • Grounded coffee grinds
  • Either notebook page of blank page
APPENDIX J

GRADE 5 ONE-ON-ONE INTERVIEW GUIDE (MAKING COFFEE ANALOGY)
Appendix J

Predictions
1. What will happen if water is poured over the coffee beans?
   a. Encourage students to draw, write, and verbalize their explanation

2. What will happen if water is poured over coffee grounds?
   a. Encourage students to draw, write, and verbalize their explanation

Observation
3. What happened when water was poured over a) the coffee beans and b) coffee grounds
   a. Probe students to discuss differences in particle size
   b. Probe students to discuss differences in water color
   c. Probe students to think about the impact of temperature
   d. Encourage students to revise their drawing
   e. Probe students to compare their macroscopic observations to the microscopic phenomena (what is in the fluid)
   f. Probe students to explain their drawing in detail

Reflection
4. Is this mini-experiment similar in any way to the stream table experiments you have been performing? Why or why not?
   a. Probe student to think about weathering
   b. Probe student to discuss changes in particle size
   c. Probe student to discuss the short comings of the coffee model and stream table model as it relates to weathering
APPENDIX K

GRADE 5 MODELS OF GLACIERS INSTRUCTION AND QUESTION GUIDE

Classroom interview guide during student science investigations
Appendix K

1. Provide 2 sets of trays per table (locate clear gelatin) – maybe Jello
   a. Tray 1: water full of clear gelatin or clear block
   b. Tray 2: jelly mixture with, plant life and regolith
      i. Students are to describe in pictures and words the contents of each tray
   c. Demonstrate glacier model to the whole class
   d. Glacier model probing
      i. If this was a glacier how did all this material accumulate?
      ii. Where did the material come from?
      iii. How are glaciers formed?
      iv. How do they move?
      v. How is this similar to or different than an actual glacier?
   e. Provide model of glacier moving down a ramp.
   f. Provide 2 (1 minute) videos of time lapse photography of glacier motion
      i. Ask for more details on the behaviors of glaciers

Materials
• Gelatin
• 7x Trays
• Wax paper
APPENDIX L

GRADE 5 ONE-ON ONE INTERVIEW PROTOCOL

Landforms Classroom Interview Guide administered after student science investigation
Appendix L

Weathering
1. What is weathering or how would you define weathering?
   a. Probe student(s) to recall or discuss their stream table experiments on erosion, deposition and/or flooding
   b. Probe student(s) to reflect on the coffee analogy

Erosion/Deposition
1. How would you define [erosion]?
   a. Probe student(s) for an example of the phenomena from their notebook or personal experience
   b. Probe student(s) to discuss how weathering is tied to erosion and/or deposition.
   c. Probe student(s) to discuss change in particle size as a result of rock composition, rock properties and climate

2. How would you define [deposition]?
   a. Probe student(s) for their understanding of sediment
   b. Probe student(s) on their understanding of soil

3. Do you have a picture (or idea) of [erosion] and/or [deposition]?
   a. Probe student(s) to elaborate on their drawing
   b. Probe student(s) to verbally integrate different properties/characteristics into their explanation (size, structure, hardness, and shape).
   c. Probe student(s) to explain how their drawing helps explain their understanding of the phenomena
   d. Probe student(s) to compare and contrast erosion to deposition

4. How does erosion caused by water, air and glaciers differ?
   a. Probe student(s) to draw differences based on sediments (gravel, sand, silt, clay)
   b. Probe student(s) to discuss graphic tools

5. How is ice involved in the movement of material?
   a. Probe student(s) to discuss how changes in temperature and water interact with material
   b. Probe student(s) to draw or discuss how rock piece size changes over time
   c. Encourage student(s) to re-draw or add to their existing drawing
   d. Probe student(s) to discuss why we have different names for rock pieces
   e. Probe student(s) on how small rocks can become
   f. Probe student(s) on the composition of rocks

6. What forces are involved in the shaping of the Grand Canyon?
a. Probe student(s) to connect the stream table experiment to the Grand Canyon
b. Probe student(s) to discuss the relationship between forces (water motion) and invisible forces (friction, gravity, water cohesion)
c. Probe student(s) to consider changes in water velocity and its effect on erosion
d. Probe student(s) to re-draw or add to their existing drawing

7. How might your stream table model relate to explaining how the Grand Canyon was created?

8. Is the Grand Canyon still in the process of changing? Why or why not?

9. How did a change in the volume of water affect the landforms?
   a. Probe student(s) to discuss how deltas form
   b. Probe student(s) to discuss the relationship between slope and water flow
   c. Encourage student(s) to reflect on a previous drawing and or written work
APPENDIX M
GRADE 3 SOILS PRE-TEST
Appendix M

Day 1: What are your ideas about soil? (How does it feel, smell and look like?)

1. What is in soil?

2. How is soil formed (made)?

3. What does soil do?
4. Draw and label picture(s) of the soil?

What other questions do you have about soil?

1.

2.

3.

4.
APPENDIX N

GRADE 3 STUDENT WORKSHEET COMPARING MATERIAL PROPERTIES
## Appendix N

Describe in words and pictures your observations?

<table>
<thead>
<tr>
<th>Description</th>
<th>Picture</th>
<th>[Modeling Tool]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Humus</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coffee</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sponge</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX O

GRADE 3 STUDENT WORKSHEET MAKING COFFEE ANALOGY
Appendix O

Part 1: Making coffee

Describe and explain what happens when you pour water into the coffee filter?

Use this space for written explanation:

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________

Use a picture to help explain your prediction.
Part 2: Making Coffee

What happens when you pour water into the coffee filter?

Use this space for explanation:

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________
APPENDIX P

GRADE 3 STUDENT WORKSHEET MUD SMEARS
Appendix P

Mud Smear

List all the items in your mud recipe. Indicate how many scoops of each item.

<table>
<thead>
<tr>
<th>List of Materials</th>
<th># Scoops</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Observations

Mud Smear          Magnifier

Written Observation?

____________________________________________________________________
____________________________________________________________________
____________________________________________________________________
APPENDIX Q

GRADE 3 STUDENT WORKSHEET SOIL SMEARS
Appendix Q

Soils Smears

What does soil look, feel, and smell like when it is wet?

Prediction
Sand       Clay       Humus

Soil Smears

Sand       Clay       Humus

Describe and explain the results of your smear test

_____________________________________________________________________
_____________________________________________________________________
_____________________________________________________________________
_____________________________________________________________________
_____________________________________________________________________
APPENDIX R

GRADE 3 STUDENT WORKSHEET WATER HOLDING CAPACITY OF SOIL
Appendix R

Compare what will happen when you pour water into the filter containing…

<table>
<thead>
<tr>
<th>Prediction (Written)</th>
<th>Picture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td></td>
</tr>
<tr>
<td>Humus</td>
<td></td>
</tr>
</tbody>
</table>
Modeling Tool

Compare what will happen when you pour water into the filter containing...

What happens when you pour water over (Soil Type A)?

Written explanation

________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
APPENDIX S

GRADE 3 STUDENT WORKSHEET SOIL SETTLING TUBES
Appendix S

How quickly do components of soil settle in water?

<table>
<thead>
<tr>
<th>Prediction</th>
<th>Observation</th>
<th>Written Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 minutes</td>
<td>4 minutes</td>
</tr>
<tr>
<td>Sand</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Humus</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Soil settling after 24 hours

<table>
<thead>
<tr>
<th>Drawing</th>
<th>Sand</th>
<th>Clay</th>
<th>Humus</th>
</tr>
</thead>
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Written observation/explanation of why

_________________________________________________________________
_________________________________________________________________
_________________________________________________________________
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APPENDIX T

GRADE 3 STUDENT WORKSHEET MYSTERY MIXTURES
Date: January 31, 2011

Dear: Soil Scientists

We are a team of archeologist conducting a `dig` in the Appalachian mountains. We excavated soil like materials from an old building site but we are unable to identify what they are. Mr. Bedward suggested your class could help us identify there properties, components, scientific name and anything else you learned while working with these materials. We would really appreciate your help.

Sincerely,

The Archeo Collective

The Archeo Collective
Name: __________________________ Date: __________

Background Content: Information from previous discussions and or experiments working with soil.

Predictions: What do you think the mystery mixtures are? Explain why?

Mystery A: __________________________

Mystery B: __________________________
Materials: What items will you use for your experiments?

Methods: What steps will you use to identify the mystery mixtures.

Mystery A: 

Mystery B: 


Analysis: What did you identify? Explain your findings.

Mystery A:  

Mystery B:  

What new questions do you have?
Date: ____________

To: The Archeo Collective:

___________________________________________

___________________________________________

___________________________________________

___________________________________________

___________________________________________

___________________________________________
Observation/Test Key Ideas

• The 4 senses
  – touch, smell, sound, visual
  – microscope

• Interactions with the environment
  – Mixing with water
  – Air drying
  – Weathering

• Smears

• Settling Tubes

• Holding Water

• Density Test

• Other________________
APPENDIX U

GRADE 3 STUDENT POST-ASSESSMENT
Appendix U

Quiz

1) How might gardeners improve sand and clay soils for gardening?
   A. Add more clay
   B. Add humus
   C. Add more sand
   D. Water every day

2) Clayton wet a sample of local soil. The soil easily rolled into a ball. Which soil is in the sample?
   A. Humus
   B. Gravel
   C. Clay
   D. Sand

3) The texture and color of humus can be best described as
   A. Moist and dark colored
   B. Dry and reddish color
   C. Gritty and light colored
   D. None of the above

4) With the help of the following graphic define what is soil?

   ![Diagram](image.png)

   Explain: ____________________________________________
   ____________________________________________
   ____________________________________________
   ____________________________________________
What type of soil test is being used? _____________________________________________

Identify, draw and provide a brief comparison of what you might see if each soil type was seen under a magnifying glass.

Soil Type 1: _____________________________________________

Soil Type 2: _____________________________________________

Soil Type 3: _____________________________________________

Soil Type 1: _______________________________________________________________________

_________________________________________________________________________________

_________________________________________________________________________________

Soil Type 2: _______________________________________________________________________

_________________________________________________________________________________

_________________________________________________________________________________

Soil Type 3: _______________________________________________________________________

_________________________________________________________________________________

_________________________________________________________________________________
5) Fran and Cheryl are exploring soil. One sample is rough, grainy and hard. What property are they exploring?

A. Texture  
B. Smell  
C. Sound  
D. Color

6) Lauren put sand in a cup with holes in the bottom. She added water to the cup. How can Lauren record how much water the sand will hold?

A. Put the water in the settling tube  
B. Record the color of water in the cup  
C. Record how much water comes out the bottom  
D. See if the sand rolls or smears

**Challenge Section**

7) How is soil formed?

Explain: _________________________________________________

_____________________________________________________

_____________________________________________________

_____________________________________________________

8) Why is soil important?

Explain: _________________________________________________

_____________________________________________________

_____________________________________________________

_____________________________________________________

_____________________________________________________

_____________________________________________________
9) The following pictures are when sand, clay and humus were each placed then shaken in a vial of water. Identify, describe and explain what happens after 24 hours.

Soil Type 1: ____________________________

Soil Type 2: ____________________________

Soil Type 3: ____________________________

Soil Type 1 (Explain): ____________________________

Soil Type 2 (Explain): ____________________________

Soil Type 3 (Explain): ____________________________
APPENDIX V

GRADE 3 STUDENT ONE-ON-ONE INTERVIEW PROTOCOL
Appendix V

Soils Questions

1. What happened when water was poured over the coffee grounds?
   a. Probe student to discuss differences in particle size
   b. Probe student to discuss differences in water color
   c. Probe student to think about the impact of temperature
   d. Encourage student to revise their drawing
   e. Probe student to compare their macroscopic observations to the microscopic phenomena
   f. Probe students to explain their drawing in detail

2. Can you explain the differences between the smears you created?
   a. Probe student to identify the soil type
   b. Probe student to discuss why there is a difference in color
   c. Probe student to elaborate on their drawing if the Particles or Magnifier tool are not being used

3. How did your smear prediction differ from what actually happened?
   a. Probe student to add to their existing smear

4. When you mixed soil and water in each of the settling tubes what happened? Can you explain why?
   a. Probe student on the forces involved
   b. Probe student to identify the soil types
   c. Probe student on particle size and how that impacts settling
   d. Probe students to explain what happened 24 hours later

5. What were you trying to explain in this picture?
   a. Is there anything you would like to add, change, delete
   b. Offer a new blank sheet.
   c. Probe student for detail

*When probing with modeling tools
What were you trying to explain by incorporating the _______ Tool
APPENDIX W

GRADE 3 STUDENT SMALL GROUP INTERVIEW PROTOCOL (SOILS)
Appendix W

What did you think of the soils unit investigations?
What did you like about the soils unit?
What did you dislike about the soils unit?
What are you still curious about?

What is a model?

What is the relationship between plants and soil? What does this relationship look like?

OR

What would you tell your best friend about plants and soil?

How can you combine your ideas/stories in order to come up with a model of the relationship between plants and soil?

Bank of words and Symbols

1. Water    19. Embryo
2. Air      20. Roots
4. Humus    22. Magnifier
5. Plants   23. Arrow
6. Leaves   24. Particle
7. Fruit    25. Frames
8. Seed     26. Compost
9. Shoots   27. Worms
10. Buds    28. Insects
11. Pollination    29. Erosion
12. Bees     30. Deposition
14. Carbon Dioxide  32. Inorganic
15. Sunlight   33. Microorganism
16. Flowers   34. Rocks
17. Seed Pod   35. Clay
18. Stem