

Contents

Introduction	3
Approach	4
Literature review	6
Problems in understanding nanoscale	6
Critical aspects for teaching nanoscale to middle school students	7
Level of attainment of the concept of nanoscale	10
Learning strategies for conveying molecular theory related concepts	13
Analogies and metaphors as the learning strategy	17
Methods and procedures	19
Content analysis	19
The instructional strategy design	21
Classroom delivery of the instructional materials	23
Results	25
Formative evaluation processes	25
Formative evaluation results	27
Conclusions and recommendations	34
References	36

Introduction

Nanotechnology has become an increasingly important area in science and technology due to its innovative and useful applications. It has been estimated that by year 2015 the global marketplace for products that use nanotechnology will reach US\$1 trillion and employ two million workers (Arrison, 2006). That will happen about the time when today's elementary students are entering college and middle school students are entering into the work force (Edu.Inc, 2004).

Not surprisingly, the US Government Administration has made the National Nanotechnology Initiative (NNI) a top science and technology priority, and it is now recognized that education in this field should be promoted to enable a new generation of skilled workers well versed in the multidisciplinary perspectives crucial for the rapid progress in nanotechnology (The National Science and Technology Council [NSTC], 2000).

Accordingly, researchers and educators have recently stressed the importance of our children becoming "nano-literate" in order to meet the future needs in this field (NSTC, 2000). It has then become imperative to start educating our middle school students to become aware of nanotechnology, getting them interested in the field, and at the same time create a deeper understanding of the underlying concepts of nanoscience. These efforts will result in future students interested in pursuing a degree in one area related to nanotechnology, and eventually become capable to fulfill this need.

Nanotechnology is built on the foundation of nanoscience. Nanoscience is the study of phenomena on the scale of approximately one to 100 nanometers; namely nanoscale. Since nanoscale is an abstract concept and human are not able to perceive it with the naked eye, our identified problem is well described by N. Sabelli et al. (2005) as: "The problem is conceptual and practical; objects and concepts at the nanoscale are hard to visualize, difficult to describe, abstract, and their relationships to the observable world can be counterintuitive (p.3)."

Notions of scale have been identified as one of the four powerful common themes that transcend disciplinary boundaries and levels. (American Association for the Advancement

of Science [AAAS] 2006). On the other hand, and as explained by Marsh, Parkes, and Boulter, (2001), there has been very little research on children's understanding of scale. There is also a tendency of teachers of underestimating the scale aspect of representation of an object and do not spend enough time teaching scaling concepts.

This project is focused on the problems and limitations found at a middle school level related to conveying the difference in relative sizes of objects that cannot be seen with the naked eye. The goal is also to identify an adequate level of attainment of the concept of scale and in particular of nanoscale, as well as suggesting strategies that could serve as a foundation for developing instructional materials that will address the identified need.

This project is an initial part of a broader study that will continue in a doctoral dissertation. In addition, the materials developed will be the pedagogical foundation for the project mission nanoHUB. Mission nanoHUB is part of the Network for Computational Nanotechnology (NCN) that is currently developing the module mission nanoHUB focused at middle school level students. The goal of this effort is to excite students about nanotechnology, lower the barrier of entry into this topic, and simultaneously provide educators and parents more tools and techniques to introduce nanotechnology concepts to this extremely critical age group (K. Madhavan, personal communication, July 15, 2006). The ultimate goal of the project is to convey the big nano ideas (Krajcik n.d., p.29). These big nano ideas include topics such as a) size and scale, b) properties at nanoscale, c) the particulate nature of matter, d) self assembly, e) modelling and tools, and f) nature of science and technology.

The focus of this project is on size and scale. Therefore, the instructional goal is that after interacting with the materials, learners will be able to identify nanoscale objects, as different from microscale objects, and provide examples of nano-sized objects.

Approach

The framework for this project was based on two sources. One was the formative and summative evaluation reports from several museum exhibits and universities that have

produced instructional materials in the form of exhibits, websites, or other types of media:

- NanoZone at Lawrence Hall of Science, University of California, Berkeley
- Its a NanoWorld at Ithaca, New Yorks Sciencenter
- NanoSense at <http://www.nanosense.org/index.html>
- Marvelous Molecules: The Secret of Life at New York Hall of Science
- Nanotechnology at Discovery World Museum, Milwaukee WI.
- Strange Matter, a travelling exhibit and at <http://www.strangematterexhibit.com>.
- NanoKids at <http://cohesion.rice.edu/naturalsciences/nanokids/>
- Too Small to See at Ithaca, New Yorks Sciencenter
- Nanotechnology: small science, big deal at the Science Museum, London

These materials were designed to be used either in a face to face environment or in an online environment. Our purpose for reviewing these materials was to identify through their evaluation reports their learning goals, the instructional strategies that were used, and how effective these strategies resulted in conveying their learning goals.

An additional result of this initial literature review was the identification the second source for the framework of this project. It was found that some of the problems in conceptual understanding to convey the molecular theory are very closely related to the conceptual understanding problems in conveying the concept of nanoscale. The concept of atom and the particulate nature of matter are science concepts that are a) the basic conceptual framework of nanoscience, b) introduced at a middle school level within a classroom setting, and c) part of the National Science Standards. Therefore, our approach consisted on identifying through journal articles, the well documented strategies that have been used to teach some concepts related to molecular theory and how those may apply for conveying the concept of nanoscale.

The results of this literature review are presented in the following sections. Our focus was on identifying a) problems encountered in understanding the concept of nanoscale, b) critical aspects to be considered for teaching nanoscale related concepts to middle school students, c) identification of the level of attainment of the concept of nanoscale, d) learning

strategies proved to be successful while conveying concepts related to molecular theory, and in particular e) analogies and metaphors as the learning strategy for that may be applied for conveying the difference in relative sizes between nanoscale and microscale objects.

Literature review

Problems in understanding nanoscale

From surveys conducted in informal educational settings, it was found that the general public have limited knowledge and consistent misconceptions about atoms, molecules, DNA, cells, and other things the interviewees cannot see (Edu.Inc, n.d.); misconceptions such as the smallest thing that they can think of is something they can actually see (early elementary students) or objects at the microscopic scale (Holladay, 2005). Another common naive conception is the fact that most of the interviewees had no working concept of one billion and did not understand 10^{-9} (Edu.Inc). Therefore, today's middle school students do not demonstrate an adequate understanding of concepts of scale and size on the micro and the nano level (Tretter, Jones, Andre, Negishi, & Minogue, 2006). Students are unable to identify the relative sizes between micrometer-sized and nanometer-sized objects (Edu.Inc, n.d., 2004, 2005; Holladay 2005; Jones et al. 2004; Waldron, 2006).

In addition, surveys demonstrate that there are high levels of unawareness and misconceptions in relation with nanotechnology and nanoscience. Research also suggests that some students have difficulties in understanding the concept of atom. In particular, students have trouble understanding the particle nature of matter and have misconceptions about the relative sizes of atoms, molecules, viruses, cells, bacteria, etc. They are not able to distinguish between the micro and nano world. These results can further be corroborated with research done by Ben-Zvi, Eylon, and Silberstein (1986a), and Krajcik (1991), who found that students hold a continuous model of matter and assume that a single atom carries properties of the substance or material. The discovered results were similar in a more recent study done by Nakhleh, Samarapungavan, and Saglam (2005). They have found that although students knew that matter was composed of atoms and molecules, the

middle school students could not be classified as having consistent knowledge frameworks because their ideas were very fragmented. They found that some students had the conception that they could see atoms or molecules under an optical microscope in the same way they could see microbes. Their data also indicate that it was difficult for students to view solid, nongranular matter as being composed of particulate or molecular matter.

A strategy to address this problem is proposed by Edu.Inc (2005). They argue that in order to understand the concept of nanotechnology, first it is necessary to understand the word 'nano,' appreciate that there is a measure called 'nanometers,' understand the scope of 'billion,' and finally, know what a meter is. They add that to fully understand nanotechnology, students must also understand the terms such as 'matter,' 'atoms,' and 'molecule.' Moreover, students must grasp that a sub-visible size scale exists in the first place, that sub-visible objects exist in different sizes, and that scientists can manipulate matter that they cannot see.

Linn, Clement, Pulos, and Sullivan (1989) also found that topic-related training enhanced knowledge about relevant variables and resulted in reasoning changes. In the same way, Nakhleh et al. (2005). explained that students form naive frameworks at an early age based on their experiences, and eventually these frameworks are modified by exposure to formal instruction. This research shows that a child can be taught any abstract concept. It only depends on the adequate formal instruction together with the integration of previous knowledge as well as addressing misconceptions and naive conceptions.

Critical aspects for teaching nanoscale to middle school students

We have identified that middle school students may require abstract thought in order to understand the concept of nanoscale (Eylon & Linn, 1988; Inhelder & Piaget, 1958). Therefore, the learning theories that address specifically issues related to abstract thinking are the developmental genetic epistemology of Piaget, and the alternative theories of cognitive development.

The developmental perspective relates to when in the life span students attain sci-

entific concepts (Eylon & Linn, 1988). According to Piaget's cognitive development stage view (Inhelder & Piaget, 1958), young children are different kinds of learners and in general thinkers than adults. Until they reach the age of 12 or so they are not capable of reasoning as an adult and show abstract thinking. The theory of cognitive development proposed four major stages of development: the sensorimotor stage, the preoperational thought stage, the concrete operations, and the formal operations.

Our target audience would be at the beginning of the formal operations stage; this same stage continues to the adulthood. The characteristics of this stage are that persons are capable of thinking logically and abstractly. They can also reason theoretically. This means that in this stage children are capable to generate abstract propositions, multiple hypotheses and their possible outcomes are evident. Thinking becomes less tied to concrete reality (Inhelder & Piaget, 1958).

The alternative theories of cognitive development build upon Piaget's genetic epistemology. These alternative theories incorporate elements of the cognitive information processing perspective. Case (1993) suggested that the mental space, a concept similar to working memory, increases during development. He suggested that this increase occurs because of three processes: brain maturation and its resulting myelination that increase processing speed, cognitive strategies become automatic, and prior knowledge becomes more extensive and better organized (as cited in Smith and Ragan, 2005). This view proposed that it is the process of encoding that distinguishes cognitive development.

An important aspect to consider is the role of experience in specific domains. This aspect was deeply studied by Siegler (1983, as cited by Driscoll, 1994). He was focused on local description as well as on specific task requirements. He suggested that when emphasized the role of encoding, it resulted in children's construction of more advanced knowledge. Siegler (1994, as cited by Driscoll) developed a performance model for problem solving. He incorporated four steps consisting on children actively encoding the features of a problem by trial and error, monitoring these features and selecting specific rules ad hoc to the problem. Then, combining the dimensions into the rule, and executing it correctly.

A study conducted Linn et al. (1989) corroborates the role of experience in scientific domain. These researchers assessed the role of science topic instruction combined with logical reasoning strategy instruction in teaching adolescent students. They found that topic-related training enhanced knowledge about relevant variables and resulted in reasoning changes. This suggests that reasoning strategies and knowledge of the subject matter influence abstract thinking. This improvement results from student's restructuring of their naive frameworks modified by exposure to formal instruction (Nakhleh et al., 2005), and as individuals learn a new domain of science (Carey, 1986).

Eylon and Linn (1988) considered the important role that plays working memory capacity. They suggested that adequate instruction, together with learners consolidation of information into procedures, would result in learners becoming able to handle more complex problems using the same amount of processing capacity. Ben-Zvi et al. (1986a) also proposed that abstract reasoning may vary as a function of working memory demand rather than development, and therefore, if a given problem overloads working memory, students cannot reason abstractly and revert to a more concrete approach. One way to reduce this overload of working memory is by using instructional strategies that will help address misconceptions.

Another common problem in learning science are the conceptions that students may have of scientific phenomena that rarely coincide with those of expert scientists. Therefore "students lack ability to relate science studied in school to naturally occurring problems" (Songer and Linn, 1987 as cited in Eylon and Linn, 1988). Research tells us (Ben-Zvi et al., 1986a; Cocking, Mestre, & Brown, 2000) that it is something natural that a student can have previous conceptions about a certain phenomena. Some of them can be right, some of them can be incomplete and some of them can be wrong. Therefore, and as stressed by Strike and Posner (1992), these previous conceptions are part of the learner's conceptual ecology and they must be seen in interaction with other components.

Logical sequences of concepts are often not enough to change misconceptions. Students also need opportunities not only to build new explanations by developing models,

thinking about analogies and conducting experiments, but also to relate this new concepts with their previous knowledge (Carey, 2000). Students need to become aware of their misconceptions and naive conceptions and then modify their frameworks in the light of the formal instruction they have received (Nakhleh et al., 2005). For this, it is required to incorporate the learner's way of looking at the world in the development of concepts. Stepan (1991) suggests that we need to (1) identify the naive conceptions held by learners, and (2) decide on proper time and effective methods to remove those conceptions. And not only remove those conceptions, but also transform their naive ideas into more sophisticated scientific understanding, to change incorrect concepts, and to develop mental structures for unfamiliar concepts (Cocking et al., 2000).

Therefore, abstract thought is required for conveying the concept of nanoscale. Although Piaget concluded in his studies that young learners cannot show abstract thinking until they reach the formal operations stage, the alternative theories of cognitive development argue that students appear quite able to think abstractly as long as they have appropriate science knowledge of the subject matter, even if they are young and if their ideas are incomplete. Therefore, deep coverage of the topic may elicit abstract reasoning (Eylon & Linn, 1988). Thus, in order to overcome the limits of working memory capacity it is necessary to help students in their process of encoding and automatization. This could be done by adequate topic-related formal instruction, knowledge of the subject matter, reasoning and reflective strategies, feedback for self-monitoring, and integration of the new information with prior knowledge.

Level of attainment of the concept of nanoscale

Ausubel et al. (1978) defined concepts as "particular sets of objects, events, symbols, properties, or situations that can be grouped together on the basis of one or more shared characteristics and are given a common identifying label or symbol" (as cited in Newby and Stepich, 1987, p 20.). Complementing this definition, Klausmeier (1990) makes a distinction between concrete concepts and abstract concepts. He explains that concepts

that have attributes that are readily observable can be classified as concrete, and in contrast, at the abstract end of the continuum, are concepts that have verbal attributes. According to this definition, then the concept of nanoscale can be described as an abstract concept because its attribute(s) is (are) intangible.

For defining the adequate level of concept attainment for nanoscale, the framework used was Klausmeier's theory of concept development. The theory of concept development iterates principles of learning and development. According to Klausmeier (1990), this theory describes how a given concept is attained at four successively higher levels of understanding. The theory also specifies the cognitive processes involved in attaining each level of the concept, indicates the uses made of the concept when attained at each level and specifies the instructional conditions that facilitate learning at each level. There are four levels of understanding in which a concept can be attained, as described in table 1.

Table 1: Klausmeier's levels of concept attainment.

Level	Description
Concrete level	A concept is attained when an item is discriminated as an entity different from its surrounds and then later is recognized as the same entity when still in the same spatial orientation or other context.
Identity level	Attainment of a concept at the identity level is inferred when the individual recognizes an item as the same one previously encountered when the item is observed in a different spatial orientation or other context.
Classificatory level	This level of a concept is attained when two or more examples of the concept are generalized as equivalent.
Formal level	At this level the concept is attained when the concept is identified and its attributes are named, a definition of the word is provided in terms of its attributes and can classify examples from non-examples.

By analyzing the target audience and referring to the Project 2061's benchmarks of the American Association for the Advancement of Science (AAAS) and National Assessment of Scientific Progress (NAEP) of the Institute of Education Sciences of the U.S. Department of Education, it was identified that between grades 6 through 8, students are starting to get

familiar with very large and very small numbers, ratios, and working with powers of ten. The benchmarks also emphasize that "understanding the notion that things necessarily work differently on different scales is more difficult than recognizing extremes, hence students should study a variety of different examples" (AAAS, 2006). It is on grade 9 through 12 when students experience a facility while using powers of ten and therefore can make it easier to describe great differences of scale, but not necessarily to make them comprehensible.

In addition, and according to the science section of the National Assessment of Scientific Progress (NAEP, 2005), at grade 8 in 2005, 59% of students scored at or above the *basic* level and 29% of eighth-grade students performed at or above the *proficient* level. From descriptions provided by the National Assessment of Scientific Progress, it is only at the *proficient* level when students at the end of their middle school have an emerging understanding of the particulate nature of matter, and at the *advanced* level have a *modest* understanding of scale (NAEP, 2005). Therefore, the level of attainment for the concept of nanoscale for middle school students was considered as acceptable if attained at a *concrete level*.

The cognitive processes required to attain a concept at the concrete level described by Klausmeier (1990) are:

- Attending to an item.
- Discriminating the item as an entity different from its surrounds on the basis of one or more of its defining attributes.
- Representing the item in long-term memory.
- Attending to and discriminating the item at a later time.
- Retrieving the representation and using it in recognizing the item as the same entity discriminated earlier.
- Storing the concrete level representation in long-term memory and being able to retrieve it.

The instructional materials were designed to address these cognitive processes in order to attain the concept of nanoscale at the concrete level.

Learning strategies for conveying molecular theory related concepts

Literature suggests the following instructional strategies as being proved to be successful in teaching the concepts of atoms and the particulate nature of matter in formal settings.

- Integration and differentiation. Integration that consists in linking consistent but unrelated conceptions and differentiation that consists of highlighting the differences between related concepts,

- analogies and metaphors to develop conceptual understanding,
- models for explaining something that is not familiar, and
- computer visualizations and simulations to represent the dynamic nature of the concepts.

We discuss how these strategies have been or could be incorporated in teaching the concept of nanoscale.

1. Integration and Differentiation.

A good way to address misconceptions is by creating a situation of cognitive dissonance leading to greater accommodation. In that way, the epistemic transition from one conceptual scheme to another could be facilitated (Eylon & Linn, 1988; Kitchener, 1992; Novick & Nussbaum, 1978). By creating a situation of conflict, a process of reflection may be elicited. Integration and differentiation are useful strategies that create a situation of conflict, and at the same time elaborate connections among ideas. These cognitive processes may result in more robust conceptual structures and avoidance of mixture of related concepts and discrimination between them (Eylon & Linn, 1988). According to Hewson and Hewson (1984, as cited in Eylon and Linn, 1988), integration links consistent but unrelated conceptions. Such linkage increases the likelihood that scientific knowledge will be remembered and facilitates reasoning. On the other hand, differentiation identifies differences between related concepts.

A successful implementation of these techniques was carried out by Ben-Zvi et

al. (1986a) in a chemistry course that was designed to assess the students' previous knowledge and at the same time to make the students aware of their misconceptions. In this implementation Ben-Zvi et al. presented the concept of an atom as an ever-evolving model, and as a result fewer students developed the misconception that an atom is a small portion of the material with the same characteristics and properties as the macroscopic one. Therefore, these two strategies are a good starting point to consider the previous knowledge and assess and/or correct the misconceptions, if any.

2. Analogies and metaphors.

Nersessian (1992a, 1992b) suggests that in order to help learners create abstractions from existing conceptual structures it should be implemented what she calls *abstraction techniques*, which consists of specific heuristic procedures such as analogies, thought experiment, limiting case analysis, and reasoning from imaginistic representations. The great advantage that analogies provide is that it is a very good way for addressing previous knowledge. They provide a method for students to become actively involved in constructing meaningful knowledge by linking previous knowledge to new concepts and restructure their conceptual understanding (Krajcik, 1991). In addition, analogies and metaphors are useful for explaining abstract science concepts in a familiar way, and when combined with models provide visual and even tactile ways of representing the phenomena (Harrison & Treagust, 2000).

Exhibits at It's a Nano World are mainly composed by analogies together with models. "Models in the context of It's a Nano World indicate object that represent sub-visible items (e.g. ball representing cells and pinballs representing dust, germs or pollen)" (Edu.Inc, 2004). The analogies together with the models served as a way of scaffolding to the visitors. The analogies represented with models used in this exhibit resulted in delivering a basal primer of concepts needed to build background for future understanding (the macro-to-micro connection), but they did not successfully make the micro-to-nano connection.

3. Models.

It has been documented (Lehrer & Schauble, 2000; Nersessian, 1992b) that experts use visual imagery like models as well as graphs, symbols and other representational systems to help them represent and understand problems and facilitate solutions.

Mayer (1992) defines a model as a representation that involves the envisionment of a principle-based mechanism with interacting components that represent the functionality or operation of a portion of the natural world and that may also concretize phenomena that are not directly observable. This technique is useful when it is required to emphasize explanations.

A model not only can be useful for abstracting from phenomena but also can help children extend their naive use of models into complex multifaceted applications (Cocking et al., 2000). However, model-based instruction must be handled carefully. Research has found that sometimes at the moment a model is used for representing something that is not familiar or cannot be seen in terms of something that is familiar or visible, children can misunderstand that the model is only a representation and actually learn the model itself. Renner and Marek (1988) stated that "In presenting concrete learners with abstract concepts such as models of atoms and molecules, what learners learn are the models rather than the concept they represent." (as cited in Stepan 1991). A good way to avoid this problem is when instructional materials cover multiple rather than isolated models (Harrison & Treagust, 2000).

This strategy is used at the exhibit of nanotechnology at Discovery World Museum to help individuals understand the size and scale of nanotechnology and how to measure structures at this size (Holladay, 2005). The main feature used for this exhibit is the hands-on exhibit based on inquiry based learning. Results from the formative assessment show that the students and adults were able to develop a deeper understanding of advanced materials concepts and were able to learn and apply the concepts contained within the exhibits (Castellini et al., 2005).

4. Computer visualization and simulation.

In the last decade the use of computer visualization and simulation tools have resulted

in a deeper understanding of the particulate nature of matter. The obvious advantage of the above mentioned techniques is the dynamic representation of the phenomena. This strategy, combined with analogies, models, etc., can result in significant understanding of abstract concepts and for its retention (Sabelli, 2006).

”This methodology is so important that it has become common in scientific discourse to consider mathematical experimentation or experimental use of computer simulations as a third leg in the triangle by now commonly used to describe the late 20th-century methodologies of science; theory and physical experimentation is no longer suffice.” (Sabelli, 2006)

Nakhleh et al. (2005) propose that the use of visualization tools and simulations together with a wider range of examples will result in a deeper understanding because in this way the phenomena is represented in a dynamic way. This increased understanding may be due to the superiority of the formation of more expert-like, dynamic mental models of a more detailed view of atomic and molecular behavior (Williamson & Abraham, 1995).

For showing the concept of size and scale, NanoZone and Marvelous Molecules have used simulations such as the zoom technique. NanoZone have used it to show magnified familiar objects, while Marvelous molecules have used it to zoom molecular structures. Edu.Inc (2005) reported that at NanoZone were evidence of visitors’ learning behavior, content acquisition, and changing attitudes, and revealed that the majority (at least 75 percent) of visitors deepened their understanding of at least one of the main content themes of the exhibition. Nonetheless, visitor comments show that significant misconceptions and partial understanding remain in visitors’ understanding of nanotechnology and other content areas after using the exhibition. This evaluation showed that a majority of visitors improved their understanding of size at the nanoscale. There was little evidence that children or adults gained an understanding of the comparative size and scale of sub-visible objects (Edu.Inc, 2004).

In the case of Marvelous Molecules, Serrell and Associates (2001) found evidence of

students recalling the big idea, as well as remembering many specifics about the individual elements. They also found that the concepts may not be comprehended by a majority of children under 12 and some of the adults.

From all these strategies, we have selected analogies and metaphors as the vehicle to convey the learning goal.

Analogies and metaphors as the learning strategy

Analogies and metaphors are a fundamental cognitive mechanisms that people use to map processes by identifying relevant information from a more familiar domain to a less familiar one (Mason, 2004). It also enables people to infer about novel phenomena, as well as to transfer learning across subject domains (Gentner and Markman, 1997; Goswami, 2001; Richland, Morrison, and Holyoak, 2006).

While analogy is a sophisticated process used in creative discovery, similarity is, as described by Gentner and Markman, (1997), brute perceptual process. Gentner (1983) define an analogy as "a device for conveying that two situations or domains share relational structure despite arbitrary degrees of difference in the objects that make up the domains. This promoting of relations over objects makes analogy a useful cognitive device, for physical objects are normally highly salient in human processing" (as cited in Gentner and Markman (1997), p.46). They emphasize the importance of common relations to analogy and not common objects. In contrast, English, (1997) describes metaphors as characterized by cross domain mappings. She explains that reasoning by metaphor implies conceptualizing the phenomena in terms of another mental domain by finding a mapping between the target domain and the source domain. "Like analogical reasoning, metaphorical reasoning can generate new inferences and lead to the construction of mental models based on the relational structure shared by the source and target." (English, 1997, p.7).

Analogies and metaphors therefore may serve as an adequate strategy for scaffolding the required students' cognitive process for attaining scale cognition. Tretter et al. (2006) describe this cognitive process as a process of unitizing. Unitizing is described as a way for

creating new meaningful units from the existing objects. Tretter et al. also suggest that students must create scale mental models focusing on relative sizes and not much on exact size information. These mental models could be based on everyday uses and conceptions of size with categorical relations. In addition, Tretter and his colleagues (2006) also suggest that conceptions of scaling must be based on experience, be organized into categories and may contain prototypes as exemplars of categories; such as landmarks and reference points.

These remarks pointed us to consider Rosch's prototype theory of concept learning. According to Rosch (1975, 1978) a concept is learned and represented as a prototype of a class of objects. A prototype of a class is an image constructed from experiences with examples of the class. The prototype includes the typical features of the class, not all of the defining attributes as the classical theory. After a prototype is formed, newly encountered instances are identified by comparison with the prototype (as cited in Klausmeier, 1990). Therefore, and as stated by (Newby & Stepich, 1987), a good way to facilitate the learning of an abstract concept would be to generate a reasonable substitute for a prototype by first transforming the attributes of the abstract concept into a more concrete form. As a result, a prototype substitute will be generated and provide a mental model based on everyday uses and conceptions of size. This prototype [analogy] is a sense-making way to unitize for making scale comparisons (Tretter et al., 2006).

From the above findings it can then be argued that scale related concepts are abstract and therefore difficult to convey at a middle school level. A proposed solution can be based the alternative theories of cognitive development, which considers that students are capable to think abstractly if limits of working memory can be overcome by appropriate science topic-related formal instruction, knowledge of the subject matter, reasoning strategies, integration of prior knowledge, and feedback. Therefore, the research question is:

Will middle school students, after being exposed to formal instruction based on cognitive information processing theory, be able to convey the relative sizes between microscale and nanoscale objects?

Methods and procedures

Content analysis

In order to establish the learning goals, it was searched which other efforts were being developed and focused on the same target audience. This search resulted in the guidance and later on collaboration with some institutions such as SRI International and their NanoSense Project and The National Center for Learning and Teaching in Nanoscale Science and Engineering [NCLT].

The NanoSense project is convening research workshops to clarify learning goals for nanoscience education and hosting teacher workshops to introduce teachers to NanoSense materials. Their working meeting brought together 44 invited experts and practitioners in nanoscience, learning science and science education to explore and debate the major concepts and learning goals for nanoscience. On the other hand, the NCLT focuses on how to support 7th through 16th graders in learning nanoscience ideas. From the NCLT, we got the content experts that reviewed the final version of the instructional materials.

Based on the learning goals proposed by SRI International together with the problems identified in the literature review, an information processing analysis was conducted (see Appendix A). It was analyzed how these learning goals fit at a middle school level and the National Science Standards (see Appendix B), the American Association for the Advancement of Science Project 2061s benchmarks, and the results of the Institute of Education Sciences (U.S. Department of education) National Assessment of Educational Progress. Together all these sources of information resulted in the structure of the materials, the potential learning objectives, the scope of this project together with its learning goal and instructional objectives, and later on the level of concept attainment. The learning goal: *conveying the difference in relative sizes between microscale and nanoscale objects* was identified as the key underlying idea of nanoscale, nanoscience, and nanotechnology to be conveyed at a middle school level.

After the content analysis was carried out, it was identified that in order to provide

a context of the concept of nanoscale, learners were first required to be introduced the concepts of nanoscience and nanotechnology. For this purpose, learners had to recall the difference between science and technology by pointing out that technology refers to the application of scientific advances while science refers to the use of the scientific method in order to derive systematized knowledge.

Then, for adequate comprehension of the new concept, prior knowledge had to be provided. Learners might require identifying the difference between size and scale, and recalling that all matter is made up of atoms and that atoms bond together to form molecules (see Figure 1).

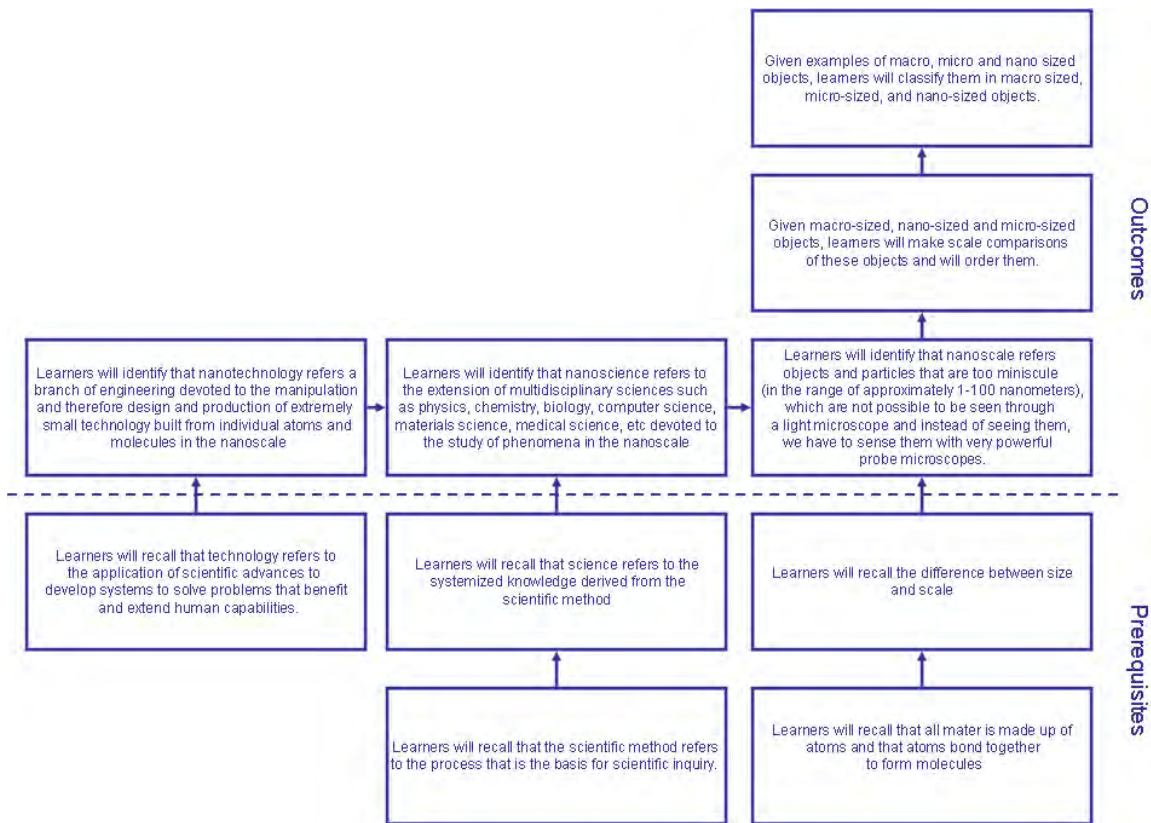


Figure 1. Instructional curriculum map for the underlying concepts of nanotechnology

Once provided the structure, the instruction required to continue by the instructor explaining the new information using the adequate learning strategies, and the students carrying out exercises and creating their own knowledge by interacting with their peers. The

process that the learners had to experience was designed as follows: 1) The learner identified that nanoscale refers to objects and particles that are too minuscule to be seen through a light microscope, instead of seeing them, we have to sense them with very powerful probe microscopes. 2) the learner identified that nanoscale objects are different from microscale objects, 3) given examples of macro, micro and nano sized objects; the learners classified them in micro sized objects, nano-sized objects and atomic-sized objects, 4) and finally, given macro-sized, nano-sized, and micro-sized objects, the learner made scale comparisons of these objects and ordered them.

The instructional strategy design

For attaining the learning goal, it was required an instructional design theory based on the cognitive information processing perspective. Therefore Gagne's theory was selected to develop instructional materials focused on intellectual skills. The instructional design based on Gagne's theory embedded and supported the learning strategy for conveying the difference in relative sizes between microscale and nanoscale objects. This theory incorporates a taxonomy, specific learning conditions, and nine events of instruction (Driscoll, 1994). In Gagne's taxonomy of learning outcomes, concepts are classified among the intellectual skills. According to Gagne, intellectual skills can be divided into five categories organized in a learning hierarchy. Our focus will be on the second type of intellectual skills, the concrete concepts, which consists of classifying new examples of events or ideas by their defining attributes (see Appendix C).

Gagne's nine events of instruction were implemented as described in Table 2.

Table 2: Structure of the materials based on Gagne’s nine events of instruction

Gaining attention	The topic was introduced by emphasizing the importance of nanotechnology. It was also described that it is thanks to new tools and techniques that scientists are able to study it. There were also mentioned some interesting applications of nanotechnology.
Informing the learner of the objective	It was described that the goal of the instruction was to understand the basic tenet of nanotechnology, which is the concept of nanoscale. It was also described the difference and relationship between nanoscience, nanotechnology, and nanoscale
Stimulating recall of prior knowledge	Two main topics were recalled in this event. Students were elicited to recall the role of atoms and molecules and conversion procedures between feet and meters. This eventually led to conversion from meters to nanometers
Presenting the stimulus and providing learner guidance	It was emphasized the difference between macroscale, microscale. Then, the analogies with the metaphor were presented.
Eliciting performance and providing feedback	A sorting activity was presented. Learners classified several objects according to their scale (micro, macro, or nanoscale). Feedback was provided.
Enhancing retention and transfer	The learner was involved in a collaborative activity consisting on creating their own analogies. A strategy for creating analogies was presented to the learners and guidance was provided during the elaboration process.
Assessing performance	For assessing performance, the student was asked to sort and order the objects in the scale. Feedback was provided.

The instruction required to provide learning and cognitive strategies in the form of those used for basic learning task that tie new information to prior knowledge; namely analogies and metaphors. Therefore, the analogies were used to scaffold the unitizing cognitive process that according to Tretter et al. (2006) is the first required cognitive process in order to attain scale cognition. This strategy created new meaningful units from the existing objects involving a proportional relationship (e.g. the difference in sizes between the height of a human and the length of an ant is approximately the same—proportional as the difference in sizes between a bacteria and the diameter of a DNA double strand).

In addition, a scale was used as a metaphor to represent powers of ten, that is, powers

of ten were considered as points on a line. This scale was used to display number sequences and scales: macroscale, microscale and nanoscale. (see Figure 2). This scale provided a graphical aid for unitizing and categorizing. Proportional analogies together with the scale metaphor were used as a way to explicitly compare two things in which their relational structure; namely their proportional sizes were emphasized.

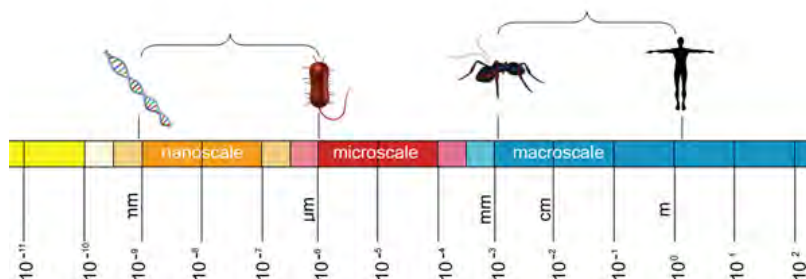


Figure 2. Example the scale metaphor and proportional analogies for conveying the relative and absolute sizes of macroscale, microscale and nanoscale objects.

Classroom delivery of the instructional materials

The delivery of the instructional materials was conducted in a 7th grade science class at a mid western middle school. The population of the seven graders at the middle school is approximately of 170 and from those, 130 were exposed to the instructional materials. This group of students was identified by the school corporation and by the seven graders science teacher. Therefore, the instructional materials were presented in an established educational setting and took place as part of normal educational practices for this group of students.

The implementation process consisted then on first getting in contact with the science teacher in charge of delivering the instruction. The researcher together with the teacher reviewed the instructional materials and the result was some modifications to the materials to fit with her teaching style. Once the science teacher got comfortable with the instructional materials, the in-class instruction was conducted. The instruction was delivered during two days consecutive one hour classes.

In order to assess student's knowledge of sizes of objects, one day before the delivery of

the instruction, students were asked to solve an exercise with two sections. The first section consisted on ordering a group of nine objects from smallest to biggest (see Appendix D). The second section asked the students to classify in three bins a group of 11 objects according to similar sizes. This section also asked the students to label each bin according to their classification.

During the first day, the instruction was delivered with the teacher explaining the concepts and the students participating in the discussion. Whenever possible, the teacher made the materials more familiar to the students and connected the content with topics they had covered in class. The scale metaphor was presented together with a conversion exercise from meters to nanometers in order to help students get more familiar with the artifact –the scale. After that, the proportional analogies together with the scale metaphor were presented and the teacher scaffolded each of the four analogies and students participated by answering the verbal cues the teacher presented. With each and every analogy the teacher emphasized the relative sizes of the objects and students were elicited to say how many times an object was smaller or bigger than the other. The first day instruction concluded with about two to three minutes for solving the classifying objects exercise (see Appendix E).

For the second day of the instruction students worked with their teams in creating their own analogies (see Appendix F). After interacting for about 20 minutes, then the group got together again and each team shared their work with the rest of the class. Immediately after that, the final assessment was administered with two exercises. The first one consisted on a group of 11 objects to be ordered but this time using the scale. In this particular exercise, three new objects were introduced, two of them were the atom and a water molecule to assess if student's understanding of the particulate nature of matter was still consistent (see Appendix G). The second one, consisted on assessing student's understanding and adequate use of the scale metaphor and the proportional analogies (see Appendix H). The researcher carried out the evaluation of the activities/assessments.

Results

Formative evaluation processes

In order to validate the effectiveness of the learning materials and at the same time to assess if the learners have achieved the learning goals, an assessment was conducted. The assessment took the form of one task analysis review by Dr. Joseph Krajcik, one design review by Dr. W. David Huang, three expert content reviews by Dr. George M. Bodner, Dr. Lynn Bryan and Cesar Delgado, one expert content level review by Mrs. Elizabeth Skelton, one review of assessment specifications by Dr. Sean Brophy, one field trial with 130 7th grade students from Wea Ridge Middle School, and classroom observations. The results are presented below.

Task analysis review. An initial version of the task analysis review was conducted by Dr. Joseph Krajcik professor of Science Education in the School of Education at the University of Michigan. He commented on the materials that the content was accurate.

Design review. Dr. W. David Huang conducted the design review. The design review was focused on content aspects such as the content supporting each instructional objective, content building on prerequisites and showing interrelationships and adequate implementation of the instructional methods and strategy. This review was also focused on the presentation of the materials. Dr. Huang focused on aspects such as adequate visuals, multiple representations of the content, and adequate use of media. Motivational aspects were also included in this design review. For a detailed version of this review see Appendix I.

Expert content review. The expert content review was conducted by experts in nanoscale science education. Dr. George M. Bodner and Dr. Lynn Bryan focused their review in the content accuracy and relevance, as well as its alignment with the *big nano ideas* together with the pedagogical approach. For a detailed version of this review see Appendix J.

Cesar Delgado is a Ph.D. science education student at University of Michigan. His research is focused on the development of students' conceptions of size and scale. His review was focused on the students' attainment of the concept level, accuracy of the content, and pedagogical approach. See Appendix K for a detailed version of this review.

Expert content level review. The expert content level review was conducted by Mrs. Elizabeth Skelton, 7th grade science teacher at the Wea Ridge Middle school. She also was in charge of giving the instruction. The purpose of this review was to identify if the students had the required entry skills and the adequate reading and language level. Also, the purpose was to align the instruction with her teaching methods.

Assessment specifications review. The assessment specification review was conducted by Dr. Sean Brophy and it had two purposes. First, to determine if the items of the tests adequately described the learning objectives it may cover, and second to verify that the tests would collect information about how the learning strategy scaffolds student's understanding of the conceptions of scale.

Field trial. The field trial involved 130 middle school science students from science classes. From these 130 students 110 completed all the set of activities and assessments as well as the two days instruction. The purpose of this evaluation was to determine the effectiveness of the materials, ascertain any problems that might arise in the administration of the materials in a real instructional environment, and validate the instruction with a large enough sample of the target audience to make a confident prediction of the effectiveness of the instructional strategy.

Classroom observation. The classroom observation was focused on how the teacher scaffolded the content to the students, student's attitudes and reactions about the topic, as well as to ascertain any problems that might arise in the administration of the materials in a real instructional environment.

Formative evaluation results

The formative evaluation results show that the instructional materials, improve students' ability to, classifying objects according to their scale, indicating they can identify the difference in relative sizes between microscale and nanoscale objects. Also, student's performance could be improved with the following changes. First, the atomic scale should be included in the main section of the instruction; namely the inclusion of the atomic scale in the scale metaphor and an analogy for addressing objects at the atomic scale. Second, the instruction must identify both the similarities between the objects (ie proportional relationship), and the relative difference between pairs of objects. Finally, learners require more opportunities to practice applying these concepts and receive feedback on their performance.

The results are presented by entry skills and learning outcomes from Table 3 through Table 10.

Entry Skills:

- a. Learners will recall that all matter is made up of atoms and that atoms bond together to form molecules.
- b. Learners will recall the difference between size and scale
- c. Learners will recall that technology refers to the application of scientific advances to develop systems to solve problems that benefit and extend human capabilities.

Learning outcomes:

- d. Learners will identify that nanoscale refers objects and particles that are too minuscule.
- e. Learners will identify nanoscale objects as different from microscale objects.
- f. Given examples of macro, micro and nano sized objects; learners will classify them in macro-sized objects, micro-sized objects and nano-sized objects.
- g. Given macro-sized, nano-sized, and micro-sized objects, learners will make scale comparisons of these objects and will order them.

Table 3: Entry skill a) Learners will recall that all matter is made up of atoms and that atoms bond together to form molecules.

Data Source	Exercise prior instruction, content level review, and assessment after second day instruction.
Information Gained	During the content level review, the science teacher validated the attainment of this entry skill. During the first sorting exercise prior to instruction, only 44% of the students showed a consistent understanding of this objective (see Figure 3). For this particular learning goal, the sample was then divided into two groups in order to assess their progression; students who reported the atom as the smallest object (44%) and students who did not report the atom as the smallest object (56%). From those students who did not selected the atom as the smallest, 64% improved their performance by selecting the atom as the smallest object after receiving the instruction. On the other hand, from the 44% how selected correctly the smallest object, only 47% repeated their correct selection. This could be because of the introduction of new objects in the after-instruction assessment. It could also be that the contrast of objects in the exercise prior instruction was clear, however, when they were faced with the nanotube and molecule they no longer thought of the atom as the smallest object showing fragmented ideas.
Revision Decision	A deeper analysis of the data is still required in order to explore the ambiguity of those students who performed inconsistently during the prior and after instruction assessments. Also, some modifications to the instructional materials are required; the teacher manual must highlight the importance of emphasizing particulate nature of matter related concepts. The atomic scale as well as an analogy comparing an atom and a molecule with two other objects in the micro and/or macro scales must also be included in the scale metaphor.

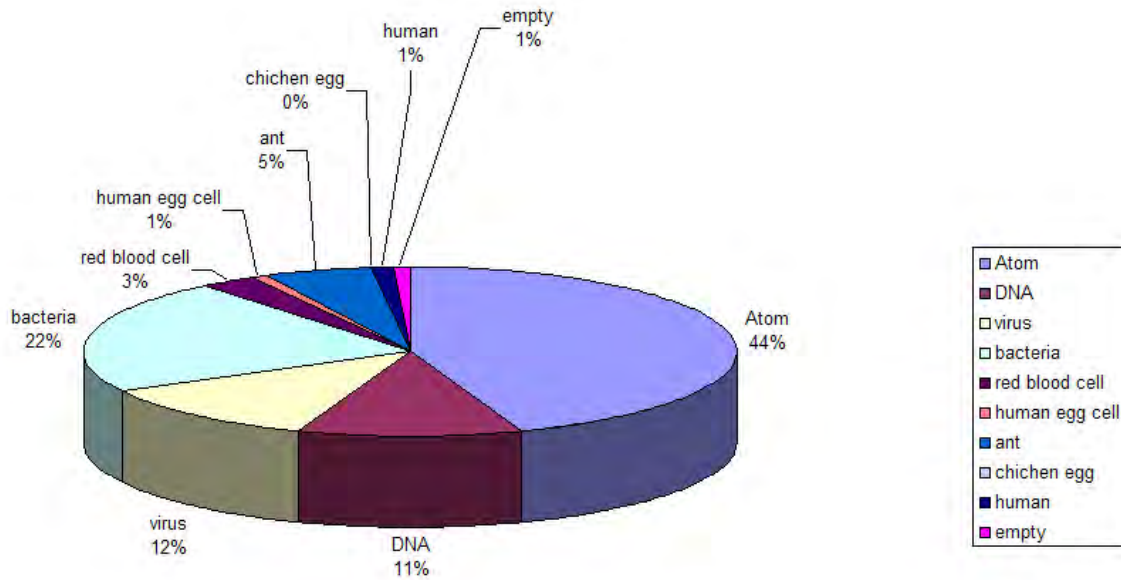


Figure 3. Smallest object selected by the students during the exercise prior to instruction

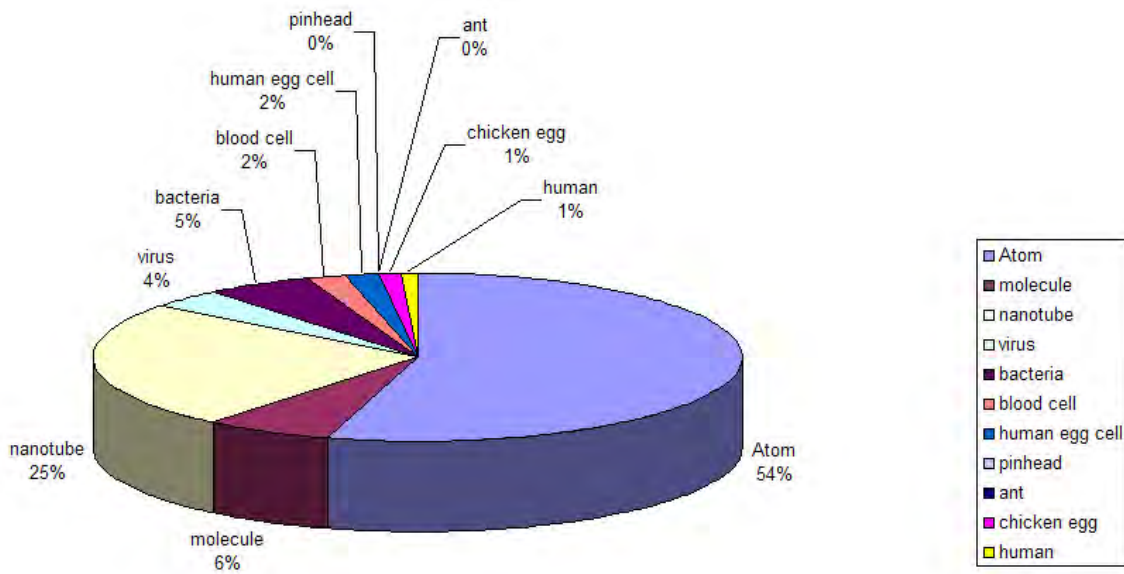


Figure 4. Smallest object selected by the students during the activity after the second day of instruction

Table 4: Learning outcome f) Given examples of macro, micro and nano sized objects; learners will classify them in macro-sized objects, micro-sized objects and nano-sized objects.

Data Source	Exercise prior to instruction and assessments conducted after the first and second day of instruction.
Information Gained	<p>The results from the exercise prior to instruction show that although more than half of the students had an acceptable notion of size and scale (i.e., those who labelled bins consistently), only the upper 10% performed accurately in classifying objects according to those labels with an average point of 0.86 in a scale from zero to one with a standard deviation of 0.06 (see Figure 5). Students showed a significant improvement after being exposed to the instruction in classifying objects according to their scale. In the exercise prior to instruction the mean was computed as 0.31 with a standard deviation of 0.31. After the first day of instruction it was then found that students improved having an overall mean of 0.82 and a standard deviation of 0.19. Finally after the second day instruction, students got an overall mean of 0.85 and a standard deviation of 0.17 (see Figure 6).</p> <p>To analyze the extreme values, 10% of the upper and lower level grading student's progression were compared through out the assessments. At the 10% lower level students scored a mean of 0.0 and a standard deviation of 0.0 in the exercise prior to instruction, and improved with a mean of 0.69 and a standard deviation of 0.18. The 10% upper level students scored a mean of 0.86 and a standard deviation of 0.062 prior to instruction and a mean of 0.97 and a standard deviation of 0.056 after instruction with 45% of students getting a perfect score. It can be suggested then, that instruction effectively helped students attain this learning objective.</p>
Revision Decision	For the fraction of students who did not attain the learning goal, it may be required more practice and feedback and/or different presentation formats. The online version of the materials will address that gap.

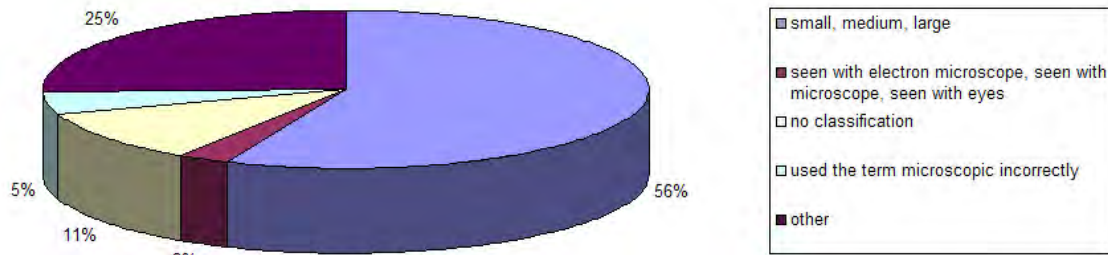


Figure 5. Categories created by the students before instruction

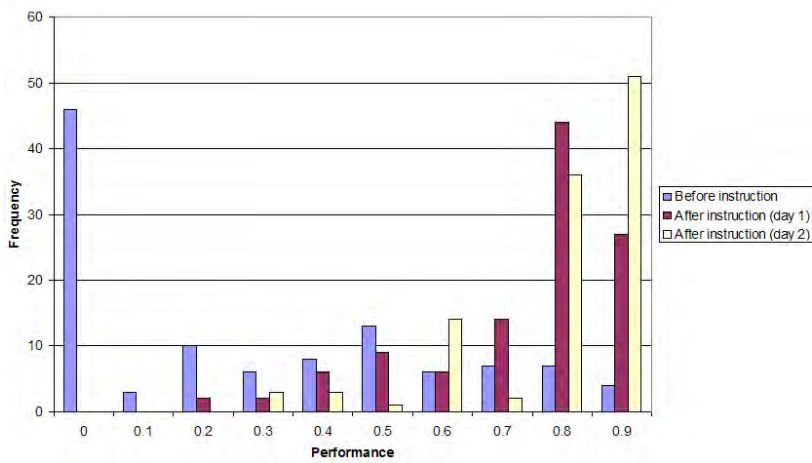


Figure 6. Comparison of objects classified by the students before and after instruction

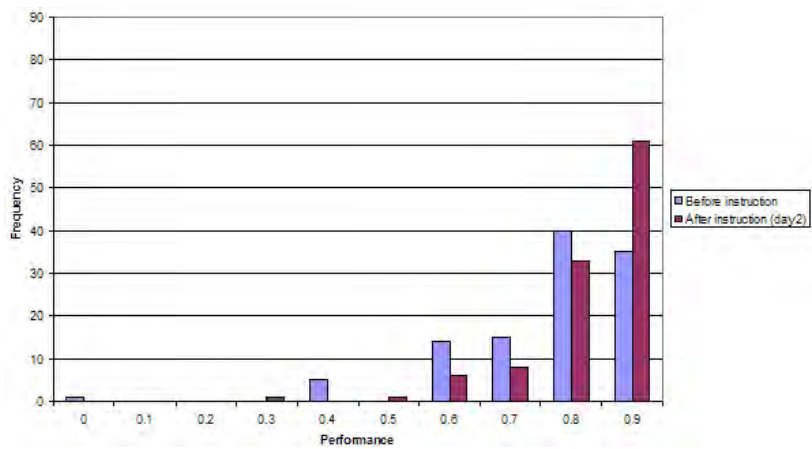


Figure 7. Comparison of objects ordered by the students before and after instruction including all objects.

Table 5: Learning outcome g) Given macro-sized, micro-sized, and nano-sized objects, learners will make scale comparisons of these objects and will order them.

Data Source	Exercise prior to instruction and assessment conducted after the second day of instruction.
Information Gained	<p>The exercise prior to instruction showed that students performed well with a mean of 0.82 in a scale from 0 to 1 and a standard deviation of 0.15. After the second day of instruction it was found that students did not have a significant improvement having a mean of 0.89 and a standard deviation of 0.10 (see Figure 7). Therefore, and just for purposes of comparison, there were just selected the objects that appeared in both assessment instruments and the means were computed again. The exercise prior to instruction showed a mean of 0.85 and a standard deviation of 0.15 compared to a mean of 0.92 and a standard deviation of 0.12 after being exposed to the instructional materials (see Figure 8). It is suggested though that the main problem for adequately ordering objects according to their scale is the lack of familiarity with the objects and knowledge of the subject matter.</p> <p>For analyzing the extremes, 10% of the upper and lower level of student's progression were compared through out the assessments. There were considered only the objects that appeared in both instruments (before and after instruction). At the 10% lower level students scored a mean of 0.49 and a standard deviation of 0.19 in the exercise prior to instruction, and improved with a mean of 0.87 and a standard deviation of 0.22. On the other hand, at the 10% upper level students scored a mean of 1.00 and a standard deviation of 0.0 prior to instruction and a mean of 0.99 and a standard deviation of 0.02 after instruction with 73% of students getting a perfect score. It can be suggested then, that instruction had a moderate impact in students who did not showed a consistent knowledge of the size of objects at the micro and nano scales prior to instruction.</p>
Revision Decision	For the fraction of students who did not attain this learning goal, it may be required more practice and feedback and/or different presentation of the content. The online version of the materials will address that gap. Materials must also be modified with the purpose of not only emphasize the proportional similarities in size among the objects being compared, but also to emphasize how they are different. In addition, it is expected that with time these students will gain a more solid knowledge of the subject matter and eventually be able to identify the relative and absolute sizes of the objects.

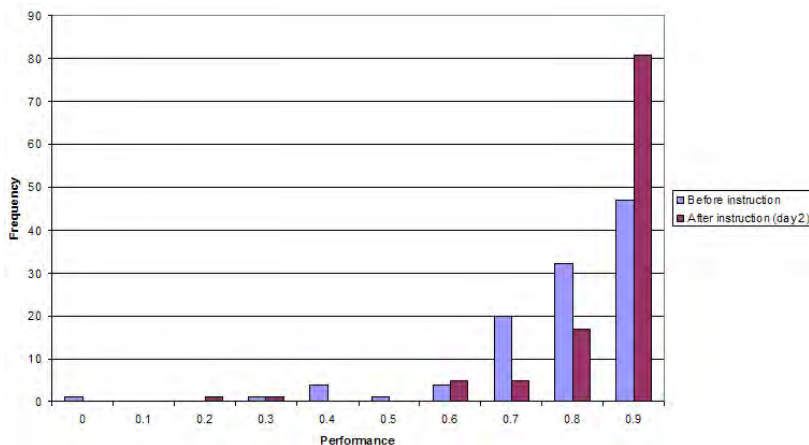


Figure 8. Comparison of objects ordered by the students before and after instruction including only the common objects in both instruments.

Table 6: Learning outcomes: All objectives

Data Source	After instruction assessments and observation.
Information Gained	Although in general the students had an improvement in their understanding of the difference in relative sizes between microscale and nanoscale objects, there were still a percentage of students that did not showed an attainment of the learning goal (approximately 12%).
Revision Decision	This can be due to factors such as the short time students were exposed for the instruction and/or the time student’s had to answer the assessment instrument after the first day of instruction (the students were answering it after the bell for their change of classes rang). This problem can be solved with longer exposure to the treatment and with multiple ways of presenting the content. The online version of the materials will fulfill this gap. Students will have plenty of opportunity for having review, practice, and immediate feedback. Another problem found is that it can be a possibility that on the final assessment students got confused with the new objects introduced. In specific with the objects that did not appear in the analogies (atom, molecule, and virus). This problem will be solved by including all the objects of the assessment in the learning strategy, and of course by introducing the atomic scale.

Table 7: Students' attitude towards the topic.

Data Source	Observation.
Information Gained	During observation it was found that most of the students showed positive attitude towards the content, but it is still required additional data to measure student's attitude towards the content.
Revision Decision	Student's attitude must be more accurately evaluated. This can be done with interviews or with surveys.

Table 8: Students' understanding of the proportional relationship of objects correct use of the scale.

Data Source	After instruction second day assessment.
Information Gained	Most of the students grasped the proportional relationships embedded in the analogies. 73% of the students were able to understand the proportional relationship represented through the analogies, to locate accurately objects on the scale by reading it, and to understand the size differences between a DNA strand and a bacteria. These two conceptions of scale are focused on student's proportional schema.
Revision Decision	None for the scope of this project, although the logical and the mathematical conceptions of scale are part of the future work.

Conclusions and recommendations

In the final analysis, it can be concluded that in order to meet the future needs in the nanotechnology field, we have to start by raising the level of awareness at a middle school level and continue by getting students interested in the field, and by conveying the underlying concepts of nanotechnology and nanoscience. Scaling related concepts have been identified as common tools between disciplines and levels as well as important unifying topics in science, engineering, and technology education.

For this reason, instructional materials were developed in order to convey the relative sizes between microscale and nanoscale objects. These materials were based on Gagne's theory and theory of concept development. In addition, analogies were selected as the vehicle to convey that two pairs of objects share a relational structure; namely their proportional sizes. In addition, a scale metaphor was used to represent powers of ten as points on a line.

Together, these two strategies served as an adequate scaffold to student's cognitive process for attaining scale cognition.

To assess the effectiveness of the materials, a formative evaluation was conducted. The results provided by the expert evaluators were positive. In general, the materials were accurate, met the requirements for the level of concept attainment at a middle school level, and were built upon an adequate pedagogical foundation. The results of the field trial also demonstrated that materials were successful in attaining the learning goal although modifications are still required.

The limitations of this study are: a) the fact that only one teacher delivered all the instructional materials, b) the assessment instruments were not designed to be compared among themselves and therefore some adjustments were required for comparison purposes and c) the data was just analyzed descriptively and a more rigorous statistical analysis may be required.

Future work includes the elaboration of a more formal study using qualitative and quantitative methods to get detailed information about student's progression in their conceptions of scale as well as their consistent and/or inconsistent understanding of the particulate nature of matter. Another interest of the researcher is to investigate how proportional analogies may scaffold the student's logical and mathematical conceptions of scale. This can include a longitudinal study in which later on the scaffold can be removed.

References

- AAAS. (2006). *American association for the advancement of science.project 2061. benchmarks on-line.* Retrieved on September 5, 2006 from: <http://www.project2061.org/publications/bsl/online/bolintro.htm>.
- Arrison, S. (2006, January). *Nanotechnology needs nano-scale regulation.* TechNewsWorld. Retrieved on September 4, 2006 from <http://www.technewsworld.com/story/48272.html>.
- Ben-Zvi, R., Eylon, B.-S., & Silberstein, J. (1986a). Revision of course materials on the basis of research on conceptual difficulties. *Studies in Educational Evaluation, 12*, 213-223.
- Carey, S. (1986). Cognitive science and science education. *American Psychologist, 41*(10), 1123-1130.
- Carey, S. (2000). Science education as conceptual change. *Journal of Applied Developmental Psychology, 21*(1), 13-19.
- Castellini, O. M., Holladay, C. E., Theim, T., Walejko, G. K., Zenner, G. M., Krajniak, P., et al. (2005). Teaching what you can't see: Museum exhibits as a bridge to learning materials science. In (Vol. 909E). Proceedings articles from Symposium PP from the 2005 MRS Fall Meeting.
- Cocking, R. R., Mestre, J. P., & Brown, A. L. (2000). New developments in the science of learning: Using research to help students learn science and mathematics. *Journal of Applied Developmental Psychology, 21*(1), 1-11.
- Driscoll, M. P. (1994). *Psychology of learning for instruction.* Allyn and Bacon.
- Edu.Inc. (n.d.). *Evaluating museum visitors' readiness for and interest in learning new science.* Retrieved on May 8, 2005 from <http://www.nanozone.org/museum.htm>.
- Edu.Inc. (2004, June). *It's a nano world. a study of use. findings from a summative study.* Retrieved on May 10, 2006 from <http://eduinc.org/>.
- Edu.Inc. (2005). *Promoting public awareness of research in nanotechnology through informal science education in a science museum exhibition.* Retrieved on May 8, 2005 from <http://www.nanozone.org/museum.htm>.
- English, L. D. (1997). Analogies, metaphors, and images: vehicles for mathematical reasoning. In L. D. English (Ed.), *Mathematical reasoning analogies, metaphors, and images.*
- Eylon, B.-S., & Linn, M. C. (1988). Learning and instruction: An examination of four research perspectives in science education. *Review of Educational Research, 58*(3), 251-301.
- Gentner, D., & Markman, A. (1997). Structure mapping in analogy and similarity. *American*

Psychologist., 52(1), 45-56.

- Goswami, U. (2001). Analogical reasoning in children. In D. Gentner, K. J. Holyoak, & B. N. Kokinov (Eds.), *The analogical mind. perspectives from cognitive science* (p. 437-470). Cambridge, Massachusetts. London, England: A Bradford Book The MIT Press.
- Harrison, A. G., & Treagust, D. F. (2000). Learning about atoms, molecules, and chemical bonds: A case study of multiple-model use in grade 11 chemistry. *Science Education*, 84(1), 352-381.
- Holladay, C. (2005, July). *A year in review: Internship in nanotechnology museum exhibit design*. Retrieved on May 12, 2006 from http://www.mrsec.wisc.edu/Edetc/IPSE_exhibits/about/share.html.
- Inhelder, B., & Piaget, J. (1958). *The growth of logical thinking from childhood to adolescence*. New York: Basic Books.
- Jones, M., Andre, T., Kubasko, D., Bokinsky, A., Tretter, T., Negishi, A., et al. (2004). Remote atomic force microscopy of microscopic organisms: Technological innovations for hands-on science with middle and high school students. *Science Education*, 88(1), 55-71.
- Kitchener, R. (1992). Piaget's genetic epistemology: Epistemological implications for science education. In R. A. Duschl & R. J. Hamilton (Eds.), *Philosophy of science, cognitive psychology and educational theory and practice* (p. 116-146). State University of New York Press.
- Klausmeier, H. (1990). Conceptualizing. In B. Jones & L. Idol (Eds.), *Dimensions of thinking and cognitive instruction*. (p. 93-138). Hillsdale, New Jersey: Lawrence Erlbaum Associates.
- Krajcik, J. (n.d.). *Utilizing research from teaching and learning to design and develop materials that foster in-depth understanding of science content and scientific practices*. National Center for Learning & Teaching in Nanoscale Science and Engineering. Seminar Series. Retrieved on December 4, 2006 from http://www.nclt.us/docs/NCLT_seminar_Krajcik_v2.pdf.
- Krajcik, J. (1991). Developing students' understanding of chemical concepts. In S. M. Glynn, R. H. Yeany, & B. K. Britton (Eds.), *The psychology of learning science* (p. 117-147). Hilldale, New Jersey: Lawrence Earlbaum Associates.
- Lehrer, R., & Schauble, L. (2000). Developing model-based reasoning in mathematics and science. *Journal of Applied Developmental Psychology*, 21(1), 39-48.
- Linn, M., Clement, C., Pulos, S., & Sullivan, T. (1989). Scientific reasoning during adolescence: The influence of instruction in science knowledge and reasoning strategies. *Journal of Research in Science Teaching*, 26, 171-187.
- Marsh, G., Parkes, T., & Boulter, C. (2001, June). Children's understanding of scale - the use of

- microscopes. *School science review*, 82(301), 27-31.
- Mason, L. (2004). Fostering understanding by structural alignment as a route to analogical learning. *Instructional Science*, 32, 293-318.
- Mayer, R. E. (1992). Knowledge and thought: Mental models that support scientific reasoning. In R. A. Duschl & R. J. Hamilton (Eds.), *Philosophy of science, cognitive psychology and educational theory and practice* (p. 226-243). State University of New York Press.
- NAEP. (2005). *National assessment of scientific progress. national and state science assessment results*. Retrieved on May 24, 2006 from <http://nces.ed.gov/nationsreportcard/>.
- Nakhleh, M. B., Samarapungavan, A., & Saglam, Y. (2005). Middle school students beliefs about matter. *Journal of Research in Science Teaching*, 42(5), 581-612.
- Nersessian, N. (1992a). Constructing and instructing: The role of "abstraction techniques" in creating and learning physics. In R. A. Duschl & R. J. Hamilton (Eds.), *Philosophy of science, cognitive psychology and educational theory and practice* (p. 48-68). State University of New York Press.
- Nersessian, N. (1992b). How do scientists think? capturing the dynamics of conceptual change in science. In R. Giere (Ed.), *Cognitive models of science* (p. 3-45). University of Minnesota Press. Minneapolis, MN.
- Newby, T., & Stepich, D. (1987). Learning abstract concepts: The use of analogies as a mediational strategy. *Journal of Instructional Development*, 10(2).
- Novick, S., & Nussbaum, J. (1978). Junior high school pupils' understanding of the particulate nature of matter: An interview study. *Science Education*, 62(3), 273-281.
- NSTC. (2000, July). *National science and technology council. national nanotechnology initiative. the initiative and its implementation plan*. Washington, DC. Retrieved on August 29, 2006 from <http://www.wtec.org/loyola/nano/IWGN.Implementation.Plan/nni.implementation.plan.pdf>.
- Richland, L. E., Morrison, R. G., & Holyoak, K. J. (2006). Childrens development of analogical reasoning: Insights from scene analogy problems. *Journal of Experimental Child Psychology*, 94, 249-273.
- Sabelli, N. (2006). Complexity, technology, science and education. *The Journal of Learning Sciences*, 15(1), 5-9.
- Sabelli, N., Schank, P., Rosenquist, A., Stanford, T., Patton, C., Cormia, R., et al. (2005, October). *Science and technology education at the nanoscale* (Report of the Workshop (draft)). SRI

International.

Serrell, & Associates. (2001, July). *Marvelous molecules: The secret of life. summative evaluation.*

Retrieved on May 8, 2006 from <http://www.informalscience.org/tools/summative.html>.

Smith, P. L., & Ragan, T. J. (2005). *Instructional design* (3rd ed.). Wiley Josssey-Bass Education.

Stepans, J. (1991). Developmental patterns in students' understanding of physics concepts. In S. M.

Glynn, R. H. Yeany, & B. K. Britton (Eds.), *The psychology of learning science* (p. 89-116).

Hillsdale, New Jersey: Lawrence Earlbaum Associates.

Strike, K. A., & Posner, G. J. (1992). A revisionist thory of conceptual change. In R. A. Duschl &

R. J. Hamilton (Eds.), *Philosophy of science, cognitive psychology and educational theory and*

practice (p. 147-176). State University of New York Press.

Tretter, T., Jones, M., Andre, T., Negishi, A., & Minogue, J. (2006). Conceptual boundaries and

distances: students' and experts' concepts of the scale of scientific phenomena. *Journal of research in science teaching*, 43(3), 282-319.

Waldron, A. (2006, May). Nanotechnology in public. *Nano Today*. Retrieved on June 23, 2006 from

http://www.nanotoday.com/pdfs_nanotoday_02_2006/Opinion-Waldron.pdf, 1(2), 56.

Williamson, V. M., & Abraham, M. R. (1995). The effects of computer animation on the particulate

mental models of college chemistry students. *Journal of Research in Science Teaching*, 32(5), 521-534.