Learning Strategies for teaching nanoscale. A survey

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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 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). The National Science and Technology Council (2000) stresses that education in this field should be promoted for a new generation of skilled workers with the multidisciplinary perspectives for the rapid progress in nanotechnology. It has then become imperative to start educating our middle school students to become aware of nanotechnology and at the same time create a deeper understanding of the underlying concepts of nanoscience.

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).”

As stressed by the American Association for the Advancement of Science (1993), scaling related concepts have been identified as one of the important unifying topics to make connections between the different science disciplines, other subject matter, and across grade levels (as cited in Tretter, Jones, Andre, Negishi, and Minogue 2006).

This study is focused on the problems and limitations related to conveying the concept of nanoscale at a middle school level. Our goal is to identify which level of attainment is the most adequate for our target audience, as well as suggesting strategies that could serve as a foundation for developing instructional materials that will cover the identified need.

Approach

The framework for this survey will be based on two sources. One is the formative an summative evaluation reports from museums that have developed exhibits related to nanotechnology. The second source is literature based on well documented studies retrieved from journal articles that suggests instructional strategies for conveying the concept of atom and the particulate nature of matter. These concepts are introduced formally at our target audience level inside a classroom setting and both are part of the National Science Standards.

Several museum exhibits and universities have produced instructional materials in the form of exhibits, websites, or other types of media. These materials were designed to be used either in a face to face environment or in an online environment. From those materials, we have identified their learning goals, the instructional strategies that were used, and how effective these strategies resulted in conveying the concept of nanoscale.

The fact that we are focusing in informal education settings is due to the novelty of the field and that no evidence was found in teaching this concept to our target audience in a formal setting.

In contrast, we have found out that some of the problems in conceptual understanding to convey the molecular theory are very close related to the conceptual understanding problems in conveying the concept of nanoscale. These close related concepts are the concept of atom and the particulate nature of matter. Therefore, our approach consist on applying the well documented strategies that have been used to teach some concepts related to molecular theory and apply them for conveying the concept of nanoscale.

Critical aspects for teaching nanoscale to middle school students

We have identified that middle schools 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 thought, and at the same time will serve as a framework the instructional problem 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 scientific 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 sensomotor 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 are 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 myelinization 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.

Another theory derived form the developmental epistemology is the one proposed by Sternberg (as cited by Driscoll, 1994). For him, development was more a novice to expert shift. This shift could be risen by two elements. By feedback to provide self-monitoring and self-correcting, and by automatization that within a component set can enhance intellectual performance.

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.

In a study, Linn, Clement, Pulos, and Sullivan (1989) 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, Samarapungavan, & Saglam, 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, Eylon, and Silberstein (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.

A 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. "Current scientific conceptions and misconceptions are parts of the learner's conceptual ecology. Thus they must be seen in interaction with other components" (Strike & Posner, 1992).

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. Stepans (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).

To sum up, abstract thought is required for conveying the concept of nanoscale. 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.

Problems in understanding nanoscale

From surveys conducted in informal education settings, it was found that public in general 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 nave 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 the adequate understanding of concepts of scale and size on the micro and the nano level (Tretter et al., 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 general, surveys demonstrate that the most critical aspect in attaining this concept is the fact that there are high levels of unawareness and misconceptions in relation with nanotechnology and nanoscience.

Closely-related concepts to nanoscale that are introduced to our target audience in the classroom and also part of the National Standards are properties of matter, such as atoms, sub-atomic particles, and molecules.

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. Students at the advanced level have a modest understanding of scale. (NAEP, 2005)

Research suggests that some students have also difficulties in understanding the concept of atom. In particular, students have trouble understanding the particle nature of matter. Students 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 et al. (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 et al. (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.

Edu.Inc (2005). 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 et al. (1989) 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 nave 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 nave conceptions.

Learning strategies for understanding atoms and the particulate nature of matter for understanding nanoscale

Literature suggests the following instructional strategies have been proved to be successful in teaching the concept of atoms and the particulate nature of matter in formal settings.

1. Integration and differentiation. Integration, that consists in linking consistent but unrelated conceptions and differentiation, which consists of highlight the differences between related concepts,
2. analogies and metaphors to develop conceptual understanding,
3. models for explaining something that is not familiar, and
4. 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). One way to create a situation of conflict and therefore reflection is by the strategies of integration and differentiation. These strategies are useful for creating more robust conceptual structures and avoid that students mix related concepts and discrimination between them (Eylon & Linn, 1988).

> ”Hewson and Hewson (1984) describe teaching strategies to elaborate connections among ideas. One is integration, which attempts to link consistent but unrelated conceptions. Such linkage increases the likelihood that scientific knowledge will be remembered and facilitates reasoning. The other teaching strategy is differentiation, which attempts to identify differences between related concepts...” (Eylon & Linn, 1988).

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).

Another advantage of analogies and metaphors is that they 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).

It’s a Nano World exhibits 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 Stepans 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 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 Moleculses have used simulations such as the zoom. NanoZone have used it to show magnified familiar objects together with an activity that consist of measuring yourself in Nanometers, while Marvelous molecules have used it to zoom molecular structures.

After being exposed to instructional materials addressing the concept of nanoscale, 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.

Although visitors showed increased understanding of key science vocabulary such as cells and nano that resulted in a successful created context for future learning abut nanotechnology, some misconceptions persisted. 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.

The approach of NanoSense in their materials Size Matters and NanoKids is different in the sense that both cases are addressing their materials to be used in formal settings, but we considered it is worthwhile to be mentioned and described.

For the case of NanoSense, they have developed materials in the form of curriculum units to be downloaded from their site, and to be used in a formal classroom environment. Their main target audience are high school level students. According to Schank et al. (2005) one of the expected learning outcomes of this project is the distinction of some commonly known objects (e.g., atom, cell, protein molecule, human hair strand) in terms of their relative size, using metric units appropriately. Although this main goal was reached, observations concluded that there were some doubts on how general physical and chemical principles could apply to the nanoscale objects. There was confusion how and why smaller objects had different properties, and continued to draw on their macroscale-level knowledge to try and explain specific phenomenon at the nanoscale (Schank et al.).

The case of NanoKids is similar. It was created to provide teachers and students with materials to increase understanding of science at molecular level. The target audience are children from grades 6-8 from 11-15 year old. The approach used is by developing materials for classroom use and the strategies are mostly hands-on activities and also exercises, discussions, games, songs, imagery, and quizzes. Descriptions provided by Harris and Furuichi (2004) state the goals of the materials, which one of our particular interest is to integrate nanoscale science and technology into existing curricula. The evaluation of these materials were focused on usability and effectiveness and therefore the change in understanding was not assessed.

Conclusions and recommendations

In the final analysis, we conclude that scaling related concepts have been identified as one of the important unifying topics. We have also identified that today's middle school students do not demonstrate the adequate understanding of concepts of scale and size on the micro and the nano level. Students are unable to identify the relative sizes between micrometer-sized and nanometer-sized objects.

Abstract thought is required for conveying the concept of nanoscale. Acquiring abstract thinking is described by two perspectives. Either when reaching the formal operations stage, or by overcoming the limits of working memory capacity. Therefore, it is necessary to scaffold 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.

Our assumption then is based on the second perspective and we consider that deep coverage of a topic may elicit abstract reasoning. This coverage should include appropriate science topic related formal instruction linked with prior knowledge and the adequate addressing of misconceptions and naive conceptions. We propose that a blended combination of the successful strategies used in the informal settings to convey the concept of nanoscale together with strategies used within a classroom to convey the idea of atoms and the particulate nature of matter will result in deeper understanding of the concept of nanoscale.

The strategies are: a) integration, that consists in linking consistent but unrelated conceptions, b) differentiation, which consists of highlight the differences between related concepts, c)analogies to develop conceptual understanding, d) models for explaining something that is not familiar and e) computer visualizations and simulations to represent the dynamic nature of the concepts. These strategies are recommended be used for representing new concepts, organizing new ideas and the relationships among them and not overloading the student's information-processing capacity. By doing so, we will help students to cross step by step the bridge between the macro to micro to nano scales.

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