

## Can Nanoscience Be a Catalyst for Educational Reform?

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### Abstract

Understanding the new discoveries and technologies resulting from modern science, including nanoscale science, requires a population with a high degree of science literacy. Unfortunately, U.S. students rank near the bottom on international studies of educational performance in science and mathematics. This essay explores the implications of national initiatives to prepare students with the science and engineering knowledge necessary to function in a highly technological society and to maintain the momentum of discovery and innovation that will sustain the nation's economic prosperity. Nanoscience can serve as a catalyst to reconsider how to bring about deep reform of science education and public policy in support of science education goals.

Keywords: science education, student achievement, education reform, teacher preparation, workforce preparation

## 1. The Need

We live in a time when new technological tools have significantly improved the ability of scientific researchers to develop new products that have wide-ranging impact on our lives, from diagnosing disease to applying paint to our cars. The impact of these scientific advances requires a commensurate response in the educational community to help students develop new frameworks for making sense of the world. The current education system is not only failing to produce a populace scientifically literate enough to understand these scientific advances, it is also failing to prepare a workforce for new jobs and professions that have emerged. Moreover, as science becomes more interdisciplinary (as we have seen in areas such as global climate change, ecology, and genetics) we can no longer rely on the traditional ways of teaching science as a set of well-understood, clearly depicted, stand-alone disciplines. Advances in science and technology are blurring the lines between the individual scientific disciplines. We need to start to develop and prepare new approaches now in order to have well-understood materials and pedagogies ready when the need for them becomes critical.

An important interdisciplinary area enabled by new tools is the science and technology of the nanoscale. Perhaps the tools that have led to the biggest breakthroughs are scanning probe instruments, such as atomic force microscopes and scanning tunneling microscopes. These tools allow scientists to view and manipulate particles at the nanoscale, such as atoms and small molecules, allowing images and manipulation of

phenomena invisible to the naked eye. The manipulation of materials at the nanoscale will allow scientists and engineers to build materials and structures with novel properties. New information and technologies resulting from this research will continue to have broad societal implications that will be realized in many fields, including health care, agriculture, food, water, energy, and the environment.

New models and ways of thinking must be developed to understand the behavior of matter at this important scale. The nanoscale is small enough that many of our models for bulk substances do not accurately predict the properties of materials, but large enough that quantum calculations are prohibitively complicated. Unfortunately, our middle and high schools fail to help students develop models of how to understand properties and phenomena at different scales. For instance, our textbooks fail to address how small the nanoscale is in comparison with the microscopic and macroscopic worlds. In fact, many middle and high school students, as well as adults, have fundamental confusions regarding scale. For instance, many students believe that a virus is smaller than an atom (Tretter et al., 2006)!

The revolution that nanoscience and nanotechnology bring to diverse areas of human endeavor requires a commensurate response in the educational community to increase students' understanding of core concepts in the field. Although there are a growing number of nanoscale science and engineering programs at the undergraduate and graduate levels, there is a strong need for nanoscience education in middle school and

high school, both to increase students' scientific literacy and to prepare them for further study. It is estimated that 2 million people with knowledge of nanoscience will be needed to work in a variety of professions worldwide by the year 2015 (Roco, 2003). A major concern of the National Science Foundation (NSF) and the National Nanotechnology Initiative (NNI) is that the United States will not have the workforce or intellectual capacity to compete worldwide in nanoscience efforts. Other countries have similar concerns, and are creating initiatives to develop human capacity in nanoscale science. For example, the European Commission (2005) has defined an action plan for Europe to promote growth and jobs in nanotechnology through interdisciplinary education and training; the German Federal Ministry of Education and Research (2006) has developed a national strategy to promote education, research, and innovation in nanotechnology; and the Nanotechnology Researchers Network Center of Japan (2006) has organized a number of nanotechnology schools to train young researchers.

It is the responsibility of national, state, and local education leadership in the United States to prepare a much larger cross-section of the U.S. population with the science and engineering knowledge necessary to function in a highly technological society and to maintain the momentum of discovery and innovation that will sustain the nation's economic prosperity. But current science education in the United States is failing on many fronts. Students are not making critical gains in standardized test scores (Gonzales et al., 2004). Science education is not addressing the critical need to prepare scientists to expand U.S. scientific research efforts (Yager, 2003), and it is not making progress in

creating a scientifically literate citizenry (National Science Board, 2002). U.S. students rank near the bottom on international studies of educational performance in science and mathematics. Their dismal performance is due partly to the science textbooks currently in use. A review of middle school curriculum materials by Kesidou and Roseman (2002) showed that none of the nine middle school programs they examined were likely to enable students to meet national science standards. Their critique claimed that the materials covered many topics at a superficial level and focused on technical vocabulary. In addition, the materials did not take advantage of what we know about student learning and did not allow students to experience phenomena or representations related to important learning goals. Moreover, U.S. textbooks fail to introduce students to emerging ideas in science. In short, “Our systems of basic scientific research and education are in serious crisis...The quality of the U.S. education system...has fallen behind those of scores of other nations...at a time when vastly more Americans will have to understand and work competently with science and math on a daily basis” (U.S. Commission on National Security/21<sup>st</sup> Century, 2001).

On the basis of such findings, NSF has funded various groups to develop materials that can inform students and the general public about nanoscience and change the way science is taught in this country. In this essay, we explore the educational implications of current initiatives and the need for new educational initiatives in nanoscience. We believe that nanoscience can serve as a catalyst to reconsider how to bring about deep reform of science education and public policy in support of science education goals.

## 2. Nanoscience in Middle School and High School

Including nanoscience education in middle school and high school curricula would do more than bring nanoscience concepts “down” to this level, it would also introduce a much-needed interdisciplinary framework into highly disjointed curricula and help students build understanding of concepts and principles of nanoscale science.

Nanoscience brings together concepts from physics, chemistry, and biology, as well as related areas such as materials science, mathematics, medicine, and engineering. In contrast, science education at the high school level is conducted primarily in discipline-specific courses, with little interplay between the disciplines. High school students typically do not experience interdisciplinary science until they enter an undergraduate institution, if at all. However, we know that the study of science as disconnected disciplines does not produce strong student understanding of the core unifying scientific concepts set forth in the national standards (National Research Council, 1996) and there is an urgent need to revise the science curriculum to reflect this reality. Moreover, important ideas in nanoscience are not central to national standards and are only weakly (if at all) introduced in grades 7 - 12. Introducing nanoscience themes and applications in grades 7 - 12 would provide a way to both establish and later revisit core science concepts and view them through a different lens. Nanoscience education introduces students to emerging ideas of science and supports understanding of the interconnections between the traditional scientific domains--reflecting the “unity in nature” (Roco, 2003)

and providing compelling, real-world examples of science in action. Unfortunately, attempts to revise the science curriculum usually involve simply rearranging the sequence of topics without changing the actual content. This kind of reordering will not significantly improve the science curriculum. Another common approach is to insert examples and sidebars in science textbooks. This textbook “vignette” model often leaves these topics out of chapter summaries or assessments, leading instructors to ignore them or assign them as optional topics only, which is unlikely to provide students with a coherent understanding of science. Instead, strong connections that exist between the disciplines need to be more strongly reflected in national standards and benchmarks, and courses that have students use science concepts and principles in an interdisciplinary fashion need to be developed.

Two areas are likely to pose the greatest conceptual challenges to student understanding of core nanoscience concepts at the high school level. The first of these arises because nanoscale entities are generally difficult to both see and visualize. A large number of studies, mostly focused on learning in chemistry, document the problems students have understanding the behavior and nature of atoms and molecules (e.g., Bunce & Gabel, 2002; Nakhleh, 1992; Wu et al., 2001). We believe that understanding processes that involve creating and using nanoscale entities will pose similar difficulties for students. However, if curriculum developers make use of some of the new tools (such as scanning probe instruments) that have emerged from nanoscience, we may be able to make progress. Currently, however, these emerging technologies are not a central focus in

science textbooks.

A second challenge to student understanding results from the concepts and physical laws that govern the behavior of particles at the nanoscale. Everyday, “macro-level” experiences of how physical objects move and interact can be accurately described by Newtonian physics. However, at the nanoscale, different rules predominate. Gravity becomes negligible, while coulombic forces, quantum mechanics, and the random thermal motion of particles become central considerations. Generally, there is little in students’ experience of the physical world and their intuitive conceptions regarding aggregate matter that can apply directly to conceptualizing nanoscale phenomena. In addition, the concept that dominant forces change with scale is not in science curricula because it is not yet addressed in national standards and benchmarks, although the American Association for the Advancement of Science is planning to include ideas related to nanoscience in the next revision of the *Atlas of Scientific Literacy*.

### 3. Initiatives in Nanoscience Education

Various groups have received funding to promote the learning of nanoscience concepts and to advance initiatives in the field. Many of these groups are addressing the challenges the United States is facing to remain competitive with other nations. They are dealing with these issues by developing curriculum materials that deal with emerging science concepts, influencing policy to modify existing national standards and benchmarks, and

targeting the general public. Below we describe a few examples of innovative initiatives that are addressing these challenges.

The first National Center for Learning and Teaching in Nanoscale Science and Engineering (NCLT; [www.nclt.us](http://www.nclt.us)) in the United States is exploring ways to build national capacity in nanoscience by focusing on and exploring questions in the learning and teaching of nanoscale science through inquiry and design of materials. The mission of the center is to produce the next generation of leaders and researchers in nanoscience to keep the United States globally competitive. In NCLT, a diverse group of scientists, science educators, and learning scientists from universities including Northwestern University, the University of Michigan, Purdue University, the University of Illinois at Urbana-Champaign, and the University of Illinois at Chicago are collaborating to bring about changes in science education, particularly in grades 7 - 16.

The NanoSense project ([nanosense.org](http://nanosense.org)) seeks to bring nanoscale science to high school classrooms by way of curriculum units. The NanoSense team consists of an interdisciplinary group of chemists, physicists, nanoscientists, and educators from SRI International, San Jose State University, and San Francisco Bay Area high schools who are developing, testing, and disseminating a number of materials to help high school teachers and students understand science concepts relating to nanoscale phenomena and integrate these concepts with traditional curricula. Units available on the project website include *Size Matters*, which focuses on concepts of size and scale, unusual properties of the nanoscale,

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tools of the nanosciences, and example applications; and *Clear Sunscreen*, which focuses on interactions of light and matter and, in particular, why zinc oxide nanoparticles block ultraviolet light but are transparent to visible light. Units in development focus on how nanoscience could advance energy production (*Clean Energy*) and water treatment (*Fine Filters*).

Nanoscale Informal Science Education (NISE; [www.nisenet.org](http://www.nisenet.org)) aims to bring the research and education communities together to develop new methods and approaches to engage the general public (including school-age children) with nanoscale science and engineering. To accomplish this mission, NISE has created a number of working groups that are developing and testing approaches for introducing the nanoscale world to the public. For example, one group aims to engage adults and older youth through dialogue and deliberation around societal implications of nanoscale science, engineering, and technology. Another group is creating packages of museum exhibits, demonstrations, immersive media experiences, multimedia, and other resources to allow informal educational institutions to create custom sets of experiences for their visitors.

A core mission of nanoscience education initiatives is to prepare individuals to function and work in our society in the future. According to the NNI (National Science and technology Council, 2005), nationwide, nanotechnology may account for a trillion-dollar annual market and employ 2 million people within 10 to 15 years. The limited numbers of U.S. students who choose technical careers has led to a concern about whether the

United States will have a workforce that is educated enough to take full advantage of future career opportunities, particularly in nanoscience. The NNI aims to address such concerns by simultaneously supporting the development of world-class research and education programs and resources to achieve the full potential of nanotechnology, including a skilled workforce and the supporting infrastructure and tools to advance nanotechnology. The NNI highlights contributions to education made possible by advances in information technologies, such as the use of scientific visualizations that bridge the perceptual gaps between the nano-, micro-, and macroscales.

The preparation of these future nanotechnology workers will need to begin early in their schooling to provide a strong basis for future endeavors in science education. Students ideally should develop a strong conceptual understanding of biology, chemistry, and physics but also of the connections between the sciences. Because most science education programs do not have an interdisciplinary component, connections between the disciplines need to be made explicit. These connections could take on a variety of forms, including weaving of nanoscience concepts and applications into existing curricula, creating a capstone-type course in the senior year of high school, devoting time at the end of each year to making connections between disciplines, and identifying opportunities for high school students to take enrichment courses at a nearby university if such courses are not offered at the high school.

With the emergence of new fields of science and the movement of these emerging fields

into the classroom, it may be time for the disciplinary model to change. The artificial barriers between the classrooms of biology, chemistry, and physics fragment students' conceptions of science and limit their ability to make scientific connections in terms of underlying commonalities, which for the most part derive from molecular or other small aggregate interactions. A single course that, for example, melds chemistry, biology, and physics into a comprehensive curriculum could be a significant step in preparing individuals for the future needs of the United States. However, measurable change will not be achieved one course at a time. Our challenge is to develop tools and strategies for integrating ideas, concepts, and practices from the learning sciences by using cross-discipline (chemistry, physics, biology, and mathematics) connections in the pedagogy. The benefits of such integration are many, but only if it is affordable in terms of instructor time and motivational in terms of value added (see, for example, Werner, 1996). Achieving these benefits requires the development of tools and strategies that are accessible to teachers across science disciplines, allow for teacher control, and demonstrate learning advantages for students. In the long term, we as a society need to revamp the way science is taught in our schools by restructuring K - 12 science education and creating science curricula that focus on interdisciplinary approaches that help students build meaningful understandings of the big ideas in science--ideas that provide insight into the development of the field, explain a range of phenomena, and help them to make individual, social, and political decisions regarding science and technology.

Whatever the solution, one thing is clear: educational reform is needed to incorporate

emerging science into the curriculum at the middle and high school levels. Perhaps one way to start such educational reform is to gather together university faculty, those in the nanoscience workforce, middle and high school teachers, and policymakers to discuss and debate the various options. Coming to an informed decision about how emerging topics should be introduced into the classroom while keeping a solid foundation in the disciplines would be extremely constructive and would allow educators to move forward in a direction that has been carefully examined and discussed. In addition, the inclusion of those who currently work in the field of nanoscience would allow consideration of what is necessary in order to prepare individuals to enter the technology workforce.

#### 4. Key Challenges to Education Reform

First, a consensus on the importance of the interdisciplinarity of science needs to come to the fore. Science and technology are constantly in a state of change, and the educational system needs to change continuously to keep abreast. The individual disciplines of science are changing and merging. Likewise, science education needs to prepare students to function in society and in a workforce that has a need for experts in interdisciplinary fields. Students who are expert in chemistry alone will not be able to make the cognitive leap that accompanies nanoscience, in which knowledge of biology and physics is also necessary. To prepare nearly 2 million workers to function in the field of nanoscience, it is crucial that we begin preparing students early, so that they can think and use knowledge in an interdisciplinary fashion.

We have discussed a few of the challenges of preparing students and the public to function in a highly technological society and to maintain the momentum of discovery and innovation. Many more challenges remain, such as the following, summarized from Sabelli et al. (2005):

- Representing interactions and behaviors of concepts difficult to understand (e.g., tunneling, thermal noise, quantum effects, emergent behaviors).
- Understanding how to teach nanoscience to different audiences, at what levels and depths, and when to teach concepts within or across disciplines.
- Identifying the developmental sequence of concepts to learn in nanoscience.
- Preparing teachers to address interdisciplinary and innovative science topics such as nanoscience.
- Balancing the physical and virtual experiences and knowing when and how they work.
- Addressing how learner intuitions can be misleading.
- Resolving the tension between reality and fiction or hype.
- Developing and integrating compelling new forms of assessment into new nanoscience activities.
- Establishing quality control and criteria for good nanoscience educational experiences.
- Understanding the ethical, social, technical, and educational context of

nanoscience.

Below, we explore in more detail four specific, recurring challenges from our work to design and disseminate nanoscience curriculum, and offer some proposed approaches to address the challenges. We focus on the following challenges:

- Defining the curriculum for a new and evolving (i.e., not fully understood) area of scientific study.
- Situating an inherently interdisciplinary science within a typical high school classroom that focuses on one discipline (i.e., chemistry).
- Developing teacher support materials for content that is novel for teachers (and, in fact, for many scientists).
- Preparing preservice teachers for teaching interdisciplinary science.

#### 4.1 Challenge 1: Defining the Curriculum

Agreeing on a few core concepts and principles, or big ideas, through discussion and debate is an important first step in making sure that curricula meet the needs of the many stakeholders involved. Groups of people who need to be involved in this discussion include nanoscientists (content experts), science education researchers, teachers, technology developers, and learning scientists. Some of the big ideas in nanoscience that have been identified include the following (Krajcik et al., 2006):

1. Under certain conditions, some materials can spontaneously assemble themselves into larger structures without external intervention. This process provides a means for manipulating material at the nanoscale.
2. Concepts of size and scale form the cognitive framework used to make sense of nanoscale phenomena.
3. All matter is composed of atoms.
4. Properties of matter change at the nanoscale.
5. Nanotechnology is driven by the processes of science and engineering to solve problems.
6. Models help us understand, visualize, predict, hypothesize, and interpret data about natural and manufactured nanoscale objects and phenomena, which are by their very nature too small to see.
7. Recently developed tools allow the investigation, measurement, and manipulation of nanoscale matter atom by atom, leading to new understandings of matter and development of new structures.

In addition, learning goals that fall under the headings of these central concepts need to be made explicit, since they are not yet included in national standards. Knowing, however, that not all students will choose to further their studies of nanoscience past high school, what are the ideas that we want students to leave with?

Another issue is how to organize the curriculum: should it be topically based around

applications, organized by underlying themes, or structured around learning goals within traditional scientific disciplines? Our work suggests that organizing units around learning goals helps to ensure that students learn what is intended, by connecting students' prior knowledge to new information (Krajcik & Blumenfeld, 2006). However, research clearly shows that we also need to consider students' motivation and the context when developing materials for students (Blumenfeld et al., 2006). It is useful for students to have an understanding of how applications of nanoscience relate to their everyday lives, thereby contextualizing the concepts and making them meaningful for society. Moreover, we have found it valuable in our work to focus students' attentions on a problem in the field. Such a focus gives students motivation for learning the new ideas (Krajcik & Blumenfeld, 2006).

A third issue is finding reliable and verifiable information in a rapidly evolving area and making it accessible to learners. For example, in the literature we found numerous terminology differences and explanations that contradicted each other on various fronts regarding whether nanoscale zinc oxide particles used in new sunscreens block ultraviolet radiation by absorbing or by scattering the radiation. As with any new science, our understanding is still evolving, and there are few common frameworks available--particularly ones that are understandable at a high school level.

In response to this group of challenges, we have begun moving toward an expert-collaborative model in which curriculum developers work in close partnership with nanoscientists and teachers to develop curricular units. To make this model work, we are

identifying and developing units based on specific, engaging nanoscience applications that tie into core high school science concepts and for which we have readily available, deep scientific expertise from partner scientists.

#### 4.2 Challenge 2: Situating the Science

Curriculum developers may create nanoscience materials targeted for high school chemistry, but knowledge of physics and biology is quite helpful for both teachers and students in understanding nanoscience and its applications. Leveraging student knowledge of other disciplines, particularly in advanced classes, could not only reduce some of the burden on teachers but also help students begin to integrate their knowledge from the different disciplines. Team teaching approaches could also be effective, although coordinating such efforts adds another layer of complexity.

Another issue is how to help teachers determine where the curriculum fits with what they currently teach. Does the new curriculum delve deep enough into core science concepts so that it can replace standard units? Can it tie in at the end of current units? How do we focus strongly on the core science involved while still showing what is new and different about nanoscience? We have found it useful to provide teachers with alignment charts of where the curriculum addresses core science topics. Providing teachers with multiple ways to use the materials and a “drill-down” structure for progressively greater depth of understanding enables adjustment for different levels of students. The materials could take the form of

replacement units or small lessons that can be embedded into the traditional curriculum.

Such options might serve as short-term solutions, but they will not bring out the level of interdisciplinary thinking that is necessary. We agree with other science education reformers (e.g., Hurd, 1991; Tinker, 2006) that there is a larger need to restructure K - 12 science education and build science curricula that focus on an interdisciplinary approach to help students build meaningful understandings of the big ideas in science. For example, Robert Tinker (2006, p. 1) argues that “Introductory science education needs a radical revision and nanoscience is the new content that is needed” and that this goal “can be accomplished with integrated science courses that span two or more grades.” Paul DeHart Hurd (1991, p. 33) writes that “There is little recognition that in recent years the boundaries between the various natural sciences have become more and more blurred and major concepts more unified” and urges science educators to integrate science curricula and use thematic science instruction. Indeed, leading experts and organizations around the world are beginning to embrace this perspective. For example, the United Nations Educational, Scientific and Cultural Organization (UNESCO) has created the Integrated Science and Technology Education program to increase student interest in science and help them relate to the subject matter. In the long term, we will succeed only by restructuring the K - 12 science curriculum to take on a more interdisciplinary approach.

#### 4.3 Challenge 3: Developing Teacher Support Materials for Novel Content

Teaching nanoscience will pose challenges to most secondary science teachers who have majored in one discipline. For example, although physics teachers might feel comfortable teaching ideas related to the interaction of light with matter, few have understandings of biological processes. One solution is to develop teacher support materials for areas in which the content reaches outside teachers' expertise. Still, lack of familiarity with the content makes it difficult for teachers to stimulate discussion by asking follow-up questions and to identify and address student misconceptions. Developers must create educational materials for teachers that provide deep explanations, provide strong guidance for discussion topics and questions, and identify and highlight potential misconceptions (Davis & Krajcik, 2005). The novelty of the content, combined with the newness of the field, raises pedagogical and content demands that some teachers may not be prepared to deal with. Teachers are not able to know all the answers to students' (and their own) questions, and many questions go beyond our current understanding as a scientific community. To help teachers engage these challenges, we have recast them as opportunities to model the scientific process and provide concrete strategies for how to do so. In this way, we aim to have teachers and students experience science in action as an empowering and energizing experience rather than as an exercise in frustration.

Ongoing professional development experiences also can provide learning opportunities for teachers. Teachers could attend summer institutes or weekend workshops in which they are introduced to nanoscience concepts, tools, and phenomena. Such opportunities could include experiences with scientists (pairing up a scientist and a teacher) and team teaching in

which novice teachers observe expert teachers enacting a nanoscience lesson. The NCLT program offers such summer institutes for teachers.

Research internships for teachers could help them “get up to speed” on current nanoscience concepts and technologies. Such internships could be modeled after the successful local industry-teaching partnership, Industry Initiatives for Science and Math Education (IISME; [iisme.org](http://iisme.org)). Teachers who receive IISME fellowships participate in a 6 - to 8-week research project in a local industry, government, or university lab setting, with a stipend. Teachers network through weekly meetings, design and critique lessons developed from their research projects, and then present these lessons to others at their schools or districts during inservice training.

#### 4.4 Challenge 4: Preparing Preservice Teachers

A final challenge, which goes hand in hand with Challenge 3, is preparing preservice teachers for teaching nanoscience. Teacher preparation is already a complex situation in the United States. Requirements of No Child Left Behind (NCLB) for science testing at the elementary, middle, and secondary levels are renewing scrutiny of teacher qualifications in science. The difficulties associated with certification of teachers in an interdisciplinary field such as nanoscience are great. Teacher education programs would have to be expanded to provide interdisciplinary teaching certificates. Currently, teachers are able to gain certification in multiple disciplines, but the majority become certified in

their (one) academic major alone. One near-term solution is to have science methods courses for preservice teachers address interdisciplinary, innovative, and emerging science topics such as nanotechnology, so that teachers can help students experience science in an interdisciplinary fashion.

## 5. Further Challenges and Implications

Despite the considerable challenges, we believe it is possible and necessary to introduce new and evolving areas of science at the middle and high school levels. Cutting-edge science can be used to engage students, reinforce core science concepts, provide insight into job opportunities in the sciences, and give students a better idea of how the traditional disciplines tie together. Looking forward, nanoscale science further challenges the learning and science research community to explore new pedagogies and societal implications of this new technology.

### 5.1 Challenges to Conceptual Understanding of Nanoscience

The challenges to helping students develop an understanding of nanoscience are both conceptual and practical; objects and concepts at the nanoscale are hard to visualize, difficult to describe, and their relationships to the observable world can be counterintuitive. These difficulties suggest the need to conceptualize a continuum of scales that can represent the nonobservable phenomena in nature to help students

integrate their views of matter at all scales. These scale issues must be addressed before students can be expected to gain an understanding of more complex phenomena and properties of matter at the nanoscale. New learning technologies hold promise for helping learners develop conceptual understanding. Science educators need to take advantage of existing technology that allows students to visualize and manipulate representations of materials at the nanoscale (e.g., Tinker, 2006), and the tools of nanoscientists need to be made available to learners. For example, multiscale modeling tools used by scientists could be adapted to allow students to simulate how specific properties change as the size scale changes and to explore, for example, the importance of ratios of surface area to volume in catalysis (Sabelli et al., 2006). In addition, a learning progression explicating the order of concepts and principles from middle school through high school needs to be developed to clarify what students need to know to master future concepts. A learning progression would allow students to build deeper and more meaningful understanding of big ideas of science and explore ideas through successively more complex ways of thinking and understanding.

## 5.2 Epistemological Concerns

Some central epistemological ideas can lead to better understanding of why science at the nanoscale requires a different educational approach. Two examples of such ideas are that (1) small quantitative changes in some property can aggregate toward large *qualitative* differences and (2) all matter can be considered as individual particles, as small groups of

particles, or as large groups of particles, each entailing different scientific models and theories. Some educators may believe that these ideas make the nanoscale even less accessible to middle and high school students; however, with the right approach, students can gain some understanding of these complex ideas in middle and high school.

### 5.3 Social Implications

A discussion of the social implications of nanotechnology as part of nanoscience education is important to give students tools to help them put in perspective the significant hype, positive as well as negative, found in most public discussions of the topic. Limiting education to “show and tell” awareness demonstrations could build the hype without providing the underlying context, whether that hype extols nanotechnology’s potential or decries its dangers. These discussions should take place in the context of possible future applications of nanotechnology. They would also provide a good opportunity for students to gain experience in debating important, controversial issues, a skill that is mentioned in the National Science Education Standards (National Research Council, 1996). Clearly, citizens of the United States must have the skills necessary to make informed decisions about possible implications of nanotechnology.

## 6. Concluding Comment

To be successful, nanoscience education will need to make a sharp departure from

traditional ways of teaching. As Hsi et al. (2006) suggest, “Addressing these challenges will hopefully lead to new thinking, techniques, and partnerships between learning scientists, educators, and scientists, just as the advancement of nanoscale science, engineering, and technology has led to new disciplines, technologies, and collaborations.” The challenges are formidable, and it is only by having diverse experts work together that we will find solutions. The research community needs to carefully study this process of change and realize that some initial attempts will fail and that successful change will take years to accomplish. Such long-term, carefully studied change in science education will occur only with the collaboration and active support of all stakeholders, including policymakers and the federal government.

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