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The Big Ideas of Nanoscience

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This document is meant to clarify the significant and developmentally appropriate learning goals in nanoscience for grade 7-16 learners. Diverse audiences, including classroom teachers and nanoscientists, stand to benefit from these agreed-upon learning goals during development of classroom materials and assessment items. More importantly, for nanoscience ideas to be used in schools, they need to be a component of the recognized learning goals for the nation's youth. Our goal is not only to have new science ideas taught in schools in which traditional methods have been successful, but also in schools with diverse and disadvantaged students. If this does not occur, it would only further exacerbate the learning gap that exists between students who come from diverse and disadvantaged backgrounds and those from upper middle class backgrounds. New emerging ideas of science need to be understood by all students in our society so that everyone can share in the rewards of the new technology. In addition, identifying learning goals in nanoscience will be advantageous to colleges and universities, to help identify starting points for their undergraduate programs in nanoscience.

CHAPTER 1- Why is it important to assemble the big ideas of nanoscience?

Our world is increasingly dependent on technology. As technological advances impact more aspects of their lives, citizens must be able to consider the risks and benefits that such progress affords. In only the last decade, cell phones and the Internet have revolutionized the way people communicate and exchange information. Computer technology is prominent in both the workplace and in homes. Advances in medicine provide new methods of diagnosis and treatment of numerous conditions. From privacy concerns related to computerized data storage, to stem cell research, citizens are increasingly being called upon to make important decisions regarding science and technology.

In addition, U.S. economic prosperity is increasingly linked with technology. A larger percentage of future jobs will require technology-based skills. Currently, the demand for workers with science and engineering skills is growing five times faster than the rest of the U.S. labor force (Foley & Hersam, 2006). Therefore, it is necessary to prepare a much larger portion of the population with the science and engineering knowledge required to function in such a highly technological environment. If all people are to be prepared to participate in the production rather than only the consumption of technological advances, then science education must address a more diverse citizenry. This is especially true in a global economy.

In fact, we are not adequately shaping the kind of educational system that prepares youth to live in a world built on science and technology. In the 2000 National Assessment of Educational Progress (NAEP), less than 1/3 of U.S. students in 4th and 8th grades scored at or above proficient levels in math and science. By the 12th grade, the number of proficient students had fallen to less than 20% (Foley & Hersam, 2006). Moreover, twelfth grade students from the U.S. ranked 19th out of 21 nations in math, and 16th out of 21 nations in science on the International Math and Science Study (1999). Based on four decades of data, Hanushek and Kimko found an apparent causal relationship between K-12 scores on international science and math tests and economic productivity. This productivity increase had a significant effect on a nation's GDP growth (2000). This trend must be reversed if the U.S. is to maintain a leading edge in science and technology, and if future generations are to look forward to economic prosperity and enhanced quality of life.

THE EMERGENCE OF NANOSCIENCE AND NANOTECHNOLGY-

With the emergence of nanoscience and nanotechnology, this urgency becomes even greater. Because nanoscience represents a convergence of all science disciplines on the nanoscale, nanoscience and nanotechnology promise to have significantly greater impact on society than previous leaps in scientific knowledge. In addition, new technology has provided tools and instrumentation that have rendered the nanoscale accessible, leading to a new level of understanding of matter and the ability to manipulate it with finer control than ever before.

Because this is such a new field, debate exists about what should be included under the nanoscience and nanotechnology umbrella—the only agreement being that "very small things" are involved. Although nanoscale concepts may be addressed in particular fields and courses, education has yet to systematically address nanoscale concepts in an integrated, cross-disciplinary fashion. The basic physics of atoms and molecules, for example, is the foundation of all science; therefore, early emphasis on these concepts would likely prove beneficial for students as they study biology, chemistry, physics and earth science. Building understanding in all of these disciplines from the atomic and molecular level can facilitate the interdisciplinary connections that students need to make to understand nanoscience and other emerging science. However, education traditionally presents concepts in a discipline-defined rather than cross-disciplinary manner.

In addition, we have not necessarily been explicit about defining the nanoscale for students, teaching nanoscale concepts but not necessarily identifying them as such. Defining the nanoscale—explicitly—is not a simple task. Some define it as any structures less than 100 nm in size (NNI). Others only include structures in which at least one dimension is 1 to 100 nanometers (NNI). Some also argue that the umbrella should include larger dimensions because interesting properties and mechanisms (e.g. microfluidics) also occur on the slightly larger micron scale (Whitesides, 2003). What everyone does agree on is that small-scale behavior of matter will impact society in profound ways thus must impact science education in an equally profound manner. As a nation, it is imperative that we prepare our students such that they are scientifically literate, can play a role in securing the nation's economic prosperity, and can participate in a global, technologically advanced society.

THE PROMISE OF NANOTECHNOLOGY-

At the nanoscale, matter displays novel, often unexpected biological, chemical and physical properties. The exploitation of these unique properties promises broad impact on society. Already many industries including electronics, pharmaceuticals, cosmetics, and textiles employ nanotechnology to improve products. Examples currently on the market include flash drives, stain-resistant clothing, transparent zinc-oxide-based sunblock and scratch-resistant automobile paint (PCAST, 2005). Less than two decades ago, portable data storage devices (e.g., floppy disks) could hold less than a megabyte of data. Today, a flash drive, which is a fraction of that size, can store more than 1000x that amount of data. The newest stain and spill resistant fabrics are created by attaching organic polymers to the cotton fibers to render them hydrophobic. The polymers are so short that they cannot be felt, so the texture of the fabric is unchanged. Advances in nanotechnology make these developments possible. Within the next decade, the technical advisory group for the President's Council of Advisors on Science and Technology predict that nanotechnology will contribute to water purification, medical diagnostics, targeted drug therapies, and better solar cells. Ultimately, nanoscience and nanotechnology are expected to infiltrate the economy to such an extent that it will be impossible to define a "nanotechnology industry."

However, with the benefits of nanotechnology also come risks. Nanoscale objects are small enough to cross some biological barriers, thus familiar materials such as zinc oxide (used in sunblocks) and gold (used in dental applications) may affect living organisms differently in nanoscale form than in their bulk form. Understanding these risks is imperative. The need to characterize and to evaluate benefits and risks further argues for a scientifically literate, informed citizenry able to consider technological advances in an educated manner.

THE NEED/THE PROBLEM-

Within the next two decades, scientists, engineers and policy groups predict that technologies and products derived from nanotechnology will contribute to greater than $1 trillion each year to the world-wide economy (Roco & Bainbridge, 2001). Nearly one million workers knowledgeable in nanoscience will be required to support the predicted nanotechnology sector in this country (Roco, 2002). Thus the future economic prosperity of our nation depends on the preparation of a much larger portion of our population with the science and engineering knowledge required to function in a highly technological society. Unfortunately, most Americans do not have a high degree of scientific literacy. In fact, a number of recent international assessments provide evidence that that level is declining relative to that of many other developed countries.

The U.S. has long been the global leader in science and technology. Much of this success can be attributed to the nation's research university system, which is arguably the best in the world. The creative and innovative environments of our universities draw the brightest from all over the world to be educated. However, increasing globalization has impacted capitalization, and investment in research and development is rising in areas such as Asia and India. This movement of capital gives foreign scientists and engineers, who are educated in the U.S., less motivation to stay here. Thus the nation faces a shortage of highly prepared workers to support its needs. This needs argues for reviewing the pipeline of students specializing in STEM related disciplines, particularly with respect to historically underrepresented groups.

Although the scores of U.S. K-12 students on national mathematics and science proficiency tests have increased since 1990, most still do not reach the "proficient" level. While U.S. elementary students score near the top internationally in mathematics and science, they score near the bottom in 12th grade. Extended faltering in K-12 STEM education has led to a generation ill-prepared to enter STEM-related fields and secure the nation's leadership in science and technology. While the number of students earning a first degree in science or engineering has remained relatively constant from 1975-2003 (4% to 6%), many European countries have seen that number triple. Asian countries such as Taiwan (~8-fold) and South Korea (~6-fold) have seen far greater increases (Foley & Hersam, 2006).

THE CHALLENGE-

Incorporating any emerging scientific field into the classroom presents many challenges. As with any addition to the curriculum, new materials must be developed, and professional development must be implemented in order to prepare teachers to successfully support student learning. However, emerging science brings with it unique challenges and questions. Which topics are the most important? Which ones can and should be incorporated into the curriculum? At what grade level is it appropriate to introduce particular concepts? Where in the instructional sequence do concepts logically build on what came before and what will follow? How do new ideas connect to those already a part of the traditional science curriculum? How are these new topics prioritized relative to traditional science concepts? Determining the answers to these questions is a difficult and complex process that requires a coordinated effort between scientists, educators, researchers and policy makers.

Increasing the challenge for the educational community is the interdisciplinary nature of nanoscience, which sets it apart from the disciplines contained in a traditional grades 7-16 science curriculum. Science in American schools tends to be taught in disciplinary fashion, with emphasis on biology, chemistry or physics, rather than on concepts important across disciplines. Emphasis on cross-disciplinary concepts would arguably enable students to develop deeper conceptual understanding than is currently the case. The interdisciplinary nature of nanoscience (and other emerging science) necessitates erasure of the curricular demarcations traditionally supported in schools. As a model, science laboratories that are the source of major breakthroughs are often comprised of interdisciplinary teams (Ref). The learning goals associated with nanoscience must explicitly foster interdisciplinary connections as well as deeper understanding of fundamental, core concepts and principles.

Science changes rapidly, yet the technological advances that permeate daily life (e.g. personal computers, cell phones) are not necessarily reflected in the classroom. The well-known joke that if Rip Van Winkle's awakened in the 21st century, he'd find everything virtually unrecognizable—except schools—reflects this reality (see *Time*, 18 December, 2006). Not simply the curriculum and its learning goals, but materials, assessments, and methods do not adequately reflect the rapid changes taking place. In addition, consensus documents that define science literacy, such as the National Science Education Standards (NRC, 1996) and Benchmarks for Scientific Literacy (AAAS, 1993) have not changed for more than a decade. Thus, a strategy for making the national Standards into a living document must be developed. This is an important first step in guiding the development of new educational materials, assessments, teacher preparation practices and instructinoal methods that emphasize the problem-solving and collaboration skills necessary for participation in a global economy. Without a coordinated effort, the nation will not be able to build the intellectual infrastructure required to secure the edge in discovery and innovation required to sustain our economic prosperity.

RESPONSE TO NEED/PROBLEM-

In response to the predicted economic impact of nanoscience and nanotechnology, and the need for a skilled workforce, the U.S. government created the National Nanotechnology Initiative (NNI). One of the goals of this long-term research and development program is to educate and train "a new generation of skilled workers in the multidisciplinary perspectives necessary for rapid progress in nanotechnology" (Roco-4). To support these educational goals, the National Science Foundation has funded several groups, including Nanoscale Science Engineering Centers (NSECs), Materials Research Science and Engineering Center (MRSECs), National Nanotechnology Infrastructure Network sites (NNIN), Nanoscale Informal Science Education network (NISE), and the National Center for Learning and Teaching Nanoscale Science and Engineering (NCLT), and Nanoscience Instructional Materials Development (NIMS) projects to create materials to inform the public (and then students) about nanoscience. Members of these groups came together at the NSF nanoscience workshop held in Washington, DC in October, 2005 and sought guidance as to what major nanoscience concepts should be included in grades 7-12 educational materials. Participants also wondered how to frame these concepts in terms of learning goals, and how the learning goals in nanoscience align with national standards. In the current educational climate, schools are under increasing pressure to show that their students can succeed on high-stakes examinations aligned with Standards. But, without explicit links to the national, state or local standards, new scientific ideas are difficult to introduce into the curriculum.

Related to that is the question of *how* nanoscience is introduced. It is imperative that nanoscience not be considered a "topic" in the curriculum, but must be integrated such that nanoscience concepts are brought to the fore at appropriate points within the curriculum. In the past, emerging science topics were often taught as separate entities, and the links between traditional science ideas and new ones were not emphasized (i.e., newer topics are often taught in stand-alone units). Because they are not part of the formal curriculum, new ideas may not be well connected to traditional concepts either in their presentation or in terms of students' conceptual development, even though connections can illuminate the process of science for students as well as provide a motivation for them to learn science.

It seems clear that a better strategy would be to carefully and systematically integrate new scientific ideas into the curriculum, making it more interdisciplinary in the process. Connections between nanoscience and traditional mathematics and science must be explicit for students. These connections should be made not just within a single class, but across grades. In order to achieve this, materials must be developed that support learning core principles, while also aligning with the national, state and local standards. However, as the nanotechnology revolution was in its infancy when the Benchmarks (AAAS, 1993) and Standards (NRC, 1996) were written, many concepts critical for understanding nanoscale science were not included or explicitly specified.

While Standards and Benchmarks have been instrumental in improving science education (REF), they do not include the scientific ideas resulting from the research in emerging fields of science, which are increasingly interdisciplinary in nature. Nanoscience is one such emerging field, in which ideas from chemistry, physics, biology and mathematics are important. However, this is not how science is traditionally taught in this country. Biology, chemistry and physics are taught separately, ignoring the fact that atoms and molecules, for example, are the foundation of all science—across disciplines. In addition, instructional materials frequently do not adequately emphasize the connections between students' new knowledge and prior knowledge. Therefore, the learning goals associated with nanoscience must explicitly foster the necessary interdisciplinary connections. Because these connections have not historically been fostered at either the secondary or post-secondary level, the teachers themselves may not have made them. Therefore, these connections must be made explicit to teachers through professional development and curriculum materials.

Having a set of agreed upon learning goals for nanoscience will help ensure that all components of the educational system including curriculum, instruction, and assessment can be aligned. Alignment occurs once learning goals are clearly defined, specified, and developed. Learning goals drive state assessments that, in turn, drive the development of materials, resources and teacher education. Identifying appropriate nanoscience learning goals will allow the development of aligned science education that will provide students with the ability to explain phenomena within and between disciplines (Wilson & Berenthal, 2006). Aligning all parts of the system to learning goals fosters the development of instructional tools and resources, educational experiences for teachers, research studies, and policies that are focused on these same critical ends (NRC, 2005; Pellegrino, 2001; Wilson & Berenthal, 2006). If rationally connected and coherent within and across grades (CCMS, 2005), materials that are developed using these learning goals can help students develop a thorough understanding of the relevant scientific concepts and to see the importance of nanoscience in their lives. In order to do this, learning goals must be identified and clarified such that their meaning is transparent in all levels of the education system. Although identifying nanoscience learning goals is the first key step in the process, clarifying the learning goals is an essential next step. In order to have an aligned system the educators and researchers who are developing the assessments, instructional materials and professional development must agree on what the learning goals are as well as on what they mean.

The ideas and products of nanoscience and nanotechnology will continue to have a profound effect on the world. Because the field of nanoscience is not only focused on a single discipline, but also reflects the convergence of all scientific disciplines on the nanoscale, it promises to have broad implications on society. The continued economic prosperity and quality of life that U.S. citizens currently enjoy depends on maintaining a leadership role in science and technology. Therefore, it is urgent that the field develops consensus as to the core principles of nanoscience. This document presents the current consensus on these core principles, their related learning goals, and the relationship between these and the Standards and Benchmarks, suggesting modifications and identifying gaps. It is intended that this document inform the field in an effort to unify cross-disciplinary thinking so that nanoscience can be successfully taught in grade 7-16 classrooms sooner rather than later.

CHAPTER 2- Determining the Big Ideas: The Process

National Science Education Standards (National Research Council, 1996; herein *Standards*), Benchmarks for Science Literacy (American Association for the Advancement of Science, 1993; herein *Benchmarks*), and *Science for All Americans* (Rutherford & Alghren, 1990) argue for a scientifically literate citizenry and schools that support the development of such a populace. In turn, school districts align curriculum, instruction and assessment with selected national, state and local standards on which students' knowledge will be measured and for which teachers will be held accountable. But nanoscience concepts are not currently explicit in these national consensus documents. In an effort to create a nano-literate population, in particular, scientists, educators, researchers and curriculum developers must ask more specifically, "What does it mean to be *nano*-literate?"

The nanotechnology revolution and its emerging scientific concepts pose challenges to standards-based education in multiple ways. First, if nanoscience concepts are not explicitly addressed in the *Standards* nor are they assessed on standardized tests, then educators struggle to justify adding them to the curriculum. Yet, as argued in Chapter 1, understanding nanoscience is key to scientific literacy. Since their publication over a decade ago, the aforementioned documents have not been adequately revised to reflect advances in science and technology, nor science educators' understanding of how students learn. State standards must be revised on a periodic basis, but the national standards have no such requirement. These realities, at a basic level, argue for changing the face of the standards so that a *living document* results, one that can continually reflect emergent science and technology. The nanotechnology revolution brings with it an array of emerging topics not yet found in textbooks, thus not yet addressed in this nation's K-16 classrooms. It is important to identify which nanoscience concepts are already part of the curriculum, for content must align with standards if concepts are to be part of an aligned system. For those key concepts already in the standards, new emphasis must occur. In addition, if there are critical ideas that are missing from the standards, they must be identified and added.

But, a second challenge to current standards-based education is that curriculum developers and classroom educators must struggle to incorporate emergent concepts into an already burgeoning science curriculum. We need to determine which nanoscience ideas need to be taught in grades 7 – 12 to develop scientific literacy. Logically, if more is to be added, but the length of the school year and school day, and the time devoted to science education remain the same, then something has to be removed from the curriculum to make room for anything new. Or, as a nation, we need to build a more coherent curriculum that builds ideas across domains within a school year as well as across school years so that concepts are revisited at a sufficient level of detail.

In 2006, a series of national workshops was held to begin to address these challenges and others that arise in the process of bringing emerging science into the classroom. This chapter describes the nature of the workshops, the specific tasks undertaken, and the processes for defining "Big Ideas" in the field and their related learning goals, as participants strove to reach consensus as to the essential understandings of nanoscience and nanotechnology important for K-12 students. This chapter also compares those identified essential understandings with national Standards and Benchmarks to highlight divergence and connection points, and to identify gaps that will require revision of those consensus documents on which current science education relies. Ultimately, educational institutions must prepare a citizenry that can lead the nanoscience revolution in both science and engineering.

METHODS: The National Workshops

The series of national workshops was held for two interrelated purposes: To address the challenges of bringing emerging science into the classroom, and to create this foundation series document to inform educators, researchers, and the field of science education. In June, 2006, the National Science Foundation (NSF) funded a national workshop dedicated to identifying and reaching consensus on the key concepts, or "Big Ideas," and associated learning goals for nanoscience that would be appropriate for grade 7-12 learners. The Nanoscience Learning Goals Workshop was held jointly by the NCLT and SRI. Thirty-nine leading scientists and science educators, chosen to represent those scientific disciplines that are involved in nanoscale science and engineering research, learning sciences, and science education, participated in the workshop (Appendix A). This expert panel included both basic and applied scientists (engineers) whose research focuses on problems related to chemistry, physics or biology. The educators participating in the workshop brought expertise in learning sciences and in both formal and informal science education. People were brought together with the goal of developing consensus about the big ideas in nanoscience and how those ideas might be introduced into the science curriculum.

In August 2006, at the NCLT Faculty Nanoscale Science and Engineering Education (NSEE) Workshop, participants considered the big ideas that would be appropriate for grade 13-16 students. In January 2007, the big ideas and learning goals were presented at the National Science Foundation's K-12 & Informal Education Nanoscale Science & Engineering Education Workshop. Each of these, interwoven with iterative cycles of vetting the documents in the science community, finally result in the foundations monograph.

Big Ideas of Nanoscience: Grades 7-12

Beginning with the Nanoscience Learning Goals Workshop, participants identified and articulated the core principles of nanoscience and justified why they believe each principle to be critical to the discipline. Participants then worked to explicate the meaning of each core concept and principle, and developed related grades 7-12 learning goals to support each of the big ideas. These learning goals were elaborated by a) identifying the prior knowledge required to understand them, and b) specifying what students need to know and be able to do to adequately reflect their understanding. Finally, participants determined how these learning goals align with National Standards and Benchmarks, and identified where these documents are insufficient regarding nanoscience.

Brainstorming- Before attending the session, individuals were asked to suggest the three ideas or principles that they believed to be most important for nanoscience. Upon arriving at the meeting, members were again asked to take the first few minutes to brainstorm ideas or principles that they believed to be most important for understanding the field of nanoscience, or that are critical to the progress of the field of nanoscience. Ideas from both iterations were assembled, posted and shared among participants.

Classify the critical principles and topics- A subset of participants was charged with grouping the ideas into related categories; a dozen such categories resulted. All participants then discussed the logic of the groupings and worked to further consolidate them. A tentative consensus of six broad topic areas was reached: Size & Scale, Properties of Matter, Particulate Nature of Matter, Self-Assembly & Dominant Force, Tools & Modeling, and Technology & Society. Agreement was not unanimous as to these groupings; in fact, several points of contention arose in the discussion (elaborated later in this chapter). At this point in the process, contentious issues were left to sub-groups to discuss further, by taking in to their discussions the perspectives of the many participants in the large group. Small groups were then charged to bring back to the whole group more focused points of discussion.

Articulate and clarify the big ideas- Given the list of 6 topic areas identified as critical for understanding and advancing the field of nanoscience, participants divided into working groups, each of which focused on a single topic. Each group purposefully contained scientists, engineers, and educators. Their charge was to articulate the general topic as a principle or big idea, clarify and elaborate it, and then to provide justification for considering it a "big idea" in nanoscience. In the articulation process, participants were also to specify related concepts and possible links, and to describe the prior knowledge needed to understand the big idea.

What is meant by "Big Ideas"?

Every scientific domain is built on a set of core concepts, the understanding of which is essential to the domain. Alone or in combination, these core concepts might have shaped the development of a field, or they might be needed to explain phenomena relevant to a field, or they contribute to broader conceptual understanding that must begin with foundational ideas. Big ideas form the very core of a domain. They are critical for basic competency because deeper understanding depends on these basic ideas as the building blocks for future science understanding. Big ideas may be cross-disciplinary. That is, they may be thought of as "big ideas" in *science* rather than more narrowly conceived of as "big ideas" in chemistry or biology. In fact, the nature of big ideas in nanoscience is that they are interdisciplinary. An essential question is: "What's *new* in nanoscience that isn't adequately articulated in existing standards?" Answers to this question can guide educators, scientists, researchers, and curriculum developers as they work to introduce nanoscale science and technology into classrooms.

Although identifying the big ideas of nanoscience was the beginning point of the workshop, the goal was not to set "nanoscience" apart as a separate entity. Rather, it was to focus on what students need to know to understand nanoscience concepts, based on the notion that the nanoscale is where the largest gap in educators' and students' understanding of matter lies, in part, because it is an emerging field, and relatedly, because it isn't part of the teacher' own background knowledge nor store of curriculum materials. National Standards address macroscale and microscale concepts, but the nanoscale is virtually absent in these documents, thus in K-12 curricula.

Clarify the big idea- Working groups articulated the big ideas, but also expanded and clarified them by identifying the major concepts and principles underlying each big idea and identifying necessary prior knowledge. By stating ideas in language that appropriately described student learning, the resulting document was expected to avoid being esoteric. Rather it aimed to be accessible to those interested in nanoscience, but not necessarily with expertise in the language and ideas of nanoscience.

Vet the big ideas among participants- Working groups presented the articulation, clarification, and justification of each big idea for evaluation and discussion in the entire group. Groups also reported their decisions about the contentious issues that were raised during the classification step. At this point, more focused discussion helped the group come to a general consensus, although not unanimous agreement. Some of the more contentious issues are described in Appendix B.

Articulate related learning goals- Next, participants returned to their working groups to develop learning goals to support the concepts and principles outlined in the clarification. The learning goals themselves are derived from the big ideas of the field. Learning goals define what students are expected to know and be able to do (which often has an application component). Multiple learning goals will always be attached to each big idea and will likely span several years of instruction. They describe different aspects of the core principles and move students toward a complete and connected understanding of key concepts. Because of the interconnected nature of many scientific ideas, there may also be occasions when a single learning goal is attached to multiple big ideas.

What is meant by learning goals?

Learning goals are useful for guiding instructional design, enactment and assessment. As such, a set of coherent, focused learning goals is important when introducing new ideas into the science curriculum. Each group attempted to think in terms of learning goals by grade level (grades 7-8, 9-10 or 11-12). This task included expressing exactly what students need to know in order to meet the learning goal, and how they should be able to apply that knowledge. In addition, working groups considered what prerequisite knowledge was needed in order to understand a particular big idea, and to meet particular learning goals. Groups also considered alternative student conceptions and potential or documented difficulties (as described in research literature). Finally, groups were asked to provide a description of illustrative phenomena that relate to each learning goal. Ultimately, all of the above were again presented to the entire group for evaluation and discussion. Appendix A illustrates a single example of a big idea (Plants make their own food) and its related learning goals.

Ilustrative phenomena-

In addition, participants were asked to generate descriptions of illustrative phenomena that could be used in curriculum materials for students. Scientific research centers around efforts to explain the world as people know and experience it. Providing students with phenomena that they can personally experience gives them a parallel goal and a connection to science inquiry. Linking student experiences to instruction has been show to be a successful motivational strategy. Real-world phenomena can be used as anchoring events for instruction and can provide students with a reason to work toward desired learning goals. In particular, phenomena provide accessible contexts to which students can apply their developing scientific understandings. For example, growing plants in water alone illustrates that plants do not require an external food source in order to grow. The experiment can be altered to prove that light, carbon dioxide and water are the necessary requirements for plants to survive. In the same way, identifying familiar phenomena that illustrate aspects of the big ideas can support student learning of nanoscale science and engineering.

Link big ideas and learning goals to standards- On the final day, working groups refined the learning goals and began to identify links between existing national standards and benchmarks. Where necessary, groups suggested how standards documents might be modified to better incorporate nanoscience-related concepts. Where this was not possible, groups noted ideas that are missing and suggested other ideas or key phenomena to be added.

Refine workshop products- After the workshop, the products from the Nanoscience Learning Goals Workshop were refined by members of the organizing team and then posted on a WIKI for ongoing editing and comment by workshop participants.

Big ideas of Nanoscience- Grades 13-16

The second NCLT Faculty Workshop was held in August, 2006 at California Polytechnic State University in San Luis Obispo. The content of the workshop emphasized building a partnership with the NCLT for learning and teaching research in nanoscale science & engineering. One aspect of the workshop focused on identifying what concepts students need to know as part of a grade 13-16 nanoscale science and engineering education. In addition, participants discussed strategies for introducing nanoscience concepts into the science curriculum.

Gathering the experts- Thirty-two faculty members from seventeen different institutions participated in the workshop (Appendix B). One quarter of the participants represented community colleges; three quarters represented four-year colleges and universities.

Brainstorming- The attendees were divided into groups by discipline of expertise, which afforded groups of chemists, physicists, engineers and science educators. Each group created a list of the concepts they believed to be critical for understanding nanoscience.

Vet the big ideas amongst participants - The lists were presented to the entire group for evaluation and discussion. The final list represents the ideas for which there was a general consensus (e.g. agreement between multiple disciplines): Size & Scale, Surface-to-Volume Ratio, Quantum Mechanics, Self-Assembly, Surface-Dominated Behavior, Tools & Instrumentation/Characterization, Models & Simulation, Size-Dependent Properties and Societal Impact & Public Education.

Ongoing vetting processes

After the workshops, the products were vetted by a larger community. The big ideas from the Nanoscience Learning Goals Workshop were presented and discussed at a symposium on "Learning at the Nanoscale" at the International Conference of the

Learning Sciences in June, 2006. At the NCLT center-wide meeting in November, 2006 the "Big Ideas of Nanoscience" for grades 7-12 and grades 13-16 were presented to the community to vet the big ideas and associated learning goals. The members of NCLT and participating collaborators debated the big ideas, and attempted to reconcile the differences between the two lists. More specifically, discussion ensued as to whether the list was complete, or whether any ideas should be removed. Based upon the results of these discussions, a draft of the document was produced for presentation at the National Science Foundation's K-12 & Informal Education Nanoscale Science & Engineering Education Workshop in January, 2007. At the same time, the document was posted for review by participants in any of the previous workshops. In preparation for publication, subsequent drafts were vetted by members of the nanoscale science and engineering community, as well as high school educators.

This document

This document addresses the significant learning goals in nanoscience for grade 7-16 learners as decided through iterative cycles of expert panelists meeting, authors writing, expert panelists rereading and giving feedback, and authors revising. We do not suggest that this is the final word on nanoscience learning goals. Instead, we hope to inform the field and to open conversation about this important effort, and to help identify the research that will be needed to support the learning progressions begun to be developed. We hope that this document will enable the nanoscience community to push the research agenda in nanoscience education and will allow future in-depth conversations to guide the development of materials and assessments.

Afterword-

At AAAS, work continues on developing logical progressions of scientific ideas by creating strand maps. After attending the Nanoscience Learning Goals Workshop for grades 7-12, AAAS modified some of the related learning goals that already existed and created additional learning goals related to nanoscience.

Appendix A

An Example: A Big Idea and its related Learning Goals

"*Plants make their own food*" is one example of a big idea that brings together multiple ideas related to the complexity of living organisms, environmental science, chemistry, biochemistry, biology and physics. A single unit in school will not be able to address the complexities of this big idea—deep understanding can only be achieved over a span of several years. For this single big idea, multiple learning goals might be derived. The following are possibilities:

- By the end of 8th grade, students will know that "plants use the energy in light to make sugars out of carbon dioxide and water" (*Benchmarks* 5E1; 6-8).
- By the end of 8th grade, students will know that "one of the most general distinctions among organisms is between plants, which use sunlight to make their own food, and animals, which consume energy-rich foods" (*Benchmarks* 5A1; 6-8).
- By the end of 12th grade, students will know that the "process of photosynthesis provides a vital connection between the sun and the energy needs of living systems" (*NSES* 9-12).

The first learning goal focuses on the process of photosynthesis or *how* plants make their own food. This learning goal could be covered in curricula related to the structure and function of plants. However, it could also be addressed in a unit about energy or a unit about the chemistry of photosynthesis. The second learning goal might revolve around ecosystems or classification of organisms. Later, students may learn to connect these concepts to the flow of energy through the changes in molecular configuration during the process of photosynthesis and its relation to the ecosystem. All of these learning goals are related to the same big idea, but could be incorporated in the curriculum in a variety of ways. In sum, understanding of the big idea is likely achievable only across a number of years.

Appendix B

Contentious Issues

It is difficult to represent in print the energy and excitement of the workshops, and the degree to which both agreement and disagreement characterized each conversation. This section briefly describes some of the most contentious issues so that readers who also view them as contentious can see that their own ideas were, indeed, part of the discussion. For example, one point of disagreement involved whether tools and instruments of nanoscience and models should be grouped together as a single big idea. There was general agreement about the importance of new tools and instruments, which are one of the primary forces driving the nanotechnology revolution. And, there was agreement about the important role that models and modeling play in the progress of the field. It was whether "tools and modeling" was a single topic, given that modeling often employs tools (i.e. computer models and simulations), or whether they needed to be separate topics that created disagreement.

In the small working group conversation, in which contentious issues were further discussed in an attempt at resolution, all consitutuents acknowledged that technology, in the guise of computers with more graphical and computational power, in a large part drives the ability to model increasingly complex systems and structures. However, while models are considered to be tools that scientists use to facilitate the scientific process, the ability to create and work with models is much more than just using an instrument. It is a skill that requires knowledge that extends well beyond the existence of a new tool to the target involved and the problem that is being addressed. In fact, part of the skill is using that knowledge to choose which tool is the best to help create the model for the desired purpose. Therefore, two separate big ideas were generated, that addressed the important roles that both tools and instrumentation, and modeling play in the advancement of nanoscale science and technology.

Another issue of contention involved the question of how to categorize the importance of dominant forces and self-assembly. All participants agreed that "the forces that are dominant within interactions change with scale" is an *important* idea, but they disagreed as to whether they consider it a "big idea." Many argued that self-assembly is the big idea, and that changes in dominant forces are a sub-heading within self-assembly. Others argued the opposite. Some participants even argued that the difference in dominant forces is a property of matter that changes with scale and therefore self-assembly alone is the big idea. Still others argued that the two concepts should be separated because forces relate to *all* interactions, not just those of self-assembly. In addition, the principle that different forces dominate interactions on different scales crosses science disciplines (e.g., physics, chemistry, biology). Thus, the idea that the dominant forces change with scale is a very general principle. Much of the debate was divided along lines of domain expertise and which seemed the "bigger" idea for a particular discipline (e.g., engineering vs. basic science).

The initial whole-group discussion at the workshop ended by grouping the Dominant Forces and Self-Assembly into one category. During the initial discussions of the small working group, members agreed that self-assembly and dominant forces are undeniably linked, but should still be considered separately. The working group chose to focus on Self-Assembly and leave Dominant Forces for NCLT-SRI team to work on later.

In addition to the issue of whether forces or self-assembly is the big idea, defining self-assembly was somewhat problematic. The nanotechnology community (primarily engineers) tend define it according to nanoscale assembly, solely from a design perspective. However, at the workshop the smaller group decided to generalize the definition such that it can be applied to occurrences of self-assembly throughout the natural universe and not just nanoscale fabrication. This tension is illustrated in the table below:

Workshop	NCLT Self-Assembly Work Circle
	• Self-assembly is based on mobile structural components reorienting their physical positions and/or bonding with other components to reach a low energy equilibrium state.
• The objects involved must assemble in a predictable, organized manner.	• The components are designed or selected so that the equilibrium state of the reoriented and bonded components creates ordered structures, such as organized chains or arrays.
• When objects self-assemble to create stable bound structures, there must be net attractive electric forces bringing and holding them together.	• Once components are introduced into the self-assembly environment, they will assemble through attractive or repulsive forces between the components.
• "Certain conditions" specifies a state in which the system achieves the activation energy required to facilitate the interactions.	• Self-assembly is a result of component interactions in an environment selected to induce a designed interaction.
	• Self-assembly components retain their physical identity through the self-assembly process and after self-assembly.
• The initial components can be isolated from the assembled structure by providing the right conditions.	• Self-assembly is reversible by controlling the environment.
	• Effects of the interactions for self-assembly may vary with the length scale of the assembly.
• Only some materials are capable of self-assembling. They must possess specific characteristics (shape, charge, etc.) in order to be viable *All pieces involved in the assembly process must be capable of assembling into the organized structure.*	

The term "designed" in point 2 of the NCLT definition limits the definition of self-assembly to an engineering term. It is particularly dangerous if we include phenomena like galaxy and planetary system formation as products of self-assembly.
- Since chemists, physicists and engineers use the term "reversibility" differently, the group replaced the term with a description of the phenomenon.
- When we discuss self-assembly as being energetically favored under given conditions, an argument could be made that all exothermic reactions could be considered self-assembly, including much of synthetic chemistry. If we apply this broad definition of self-assembly, then the group thought that a list of examples of phenomena that cannot be considered self-assembly is prudent:

- Aggregation cannot be considered self-assembly because the final state is not organized.
- Catylyzed reactions (synthetic and biological (enzymes)) require interactions with objects that are not part of the final assembly.
- Likewise, chaperone-directed assemblies (biological) cannot be considered to be self-assembly.
- Traditionally manufactured objects require mechanical input and thus are not self-assembly.

CHAPTER 3: The *Big Ideas* of Nanoscience

At the Nanoscience Learning Goals Workshop, participants identified seven core principles critical for nanoscience education in grades 7-12. Independently, participants at the NCLT Faculty Workshop identified nine principles critical for grades 13-16. The overlap in the principles identified for secondary and post-secondary education is evident in the table below.

Nanoscience Learning Goal Workshop (Grades 7-12)	NCLT Faculty Workshop (Grades 13-16)
Size & Scale	Size & Scale
Properties of Matter	Size-Dependent Properties
Particulate Nature of Matter	
Tools	Tools & Instrumentation/Characterization
Modeling	Models & Simulations
Dominant Forces	Surface-Dominated Behavior
Technology & Society	Societal Impact/Public Education
Self-Assembly	Self-Assembly
	Surface-to-Volume Ratio
	Quantum Mechanics

Table 1. Core topics identified at the two workshops.

Results from the two workshops were presented in this form at the NCLT center-wide meeting in November, 2006 in order to vet the ideas and the language used to express them. Members of NCLT and participating collaborators worked to reconcile differences between the two lists, including debating the ideas and discussing whether any should be added or omitted.

The group reached consensus that Dominant Forces should be its own big idea rather than be combined with Self-Assembly. Participants also decided that Surface-to-Volume Ratio from the grades 13-16 list should be categorized under one of the other big ideas—either Size & Scale, or Properties of Matter/Size-Dependent Properties. Likewise, Surface-Dominated Behavior was subsumed by Properties of Matter/Size-Dependent Properties.

Quantum Mechanics was added as a big idea, but only for grades 13-16. The group indicated that students in grades 7-12 could be made aware that there are ways of explaining the behavior of matter other than using classical mechanics, but they should not be expected to move beyond that level of understanding. The Particulate Nature of Matter remained a big idea, but only for grades 7-12. By the time students reach the post-secondary level, they should understand the concepts contained within this big idea. Learning goals for the remaining big ideas support students' developing understanding across grades 7-16.

Throughout the process, those in attendance at each workshop reached general consensus about which concepts are important to nanoscience and nanotechnology, but no group reached unanimous agreement. Even when participants agreed on the critical concepts, they sometimes disagreed as to how they those concepts should be organized under the big ideas. Much of the difficulty lay in the fact that the big ideas are so closely inter-connected. For example, concepts of size and scale underlie all of the big ideas because size defines the nanoscale, and scale defines which laws of physics are required to explain the behavior of matter. In addition, many of the concepts are related to ideas already present in the science curriculum, so many participants did not necessarily see them as "new" or as needing definition apart from what has already been done in the Standards and Benchmarks. However, articulating these ideas in a nanoscience context universalizes them so that they can then be more clearly applied across disciplines. For example, the same types of forces that dominate the interactions between atoms also dominate the interactions between nanoscale objects whether they are natural (e.g., protein, DNA.) or fabricated (e.g., nanoparticles, nanotubes.). Therefore, a strong foundation in the structure of matter and how it is held together is imperative to understanding the properties and behavior of matter at the nanoscale. A more complete discussion of these and other points of debate can be found in the Contentious Issues section at the end of this chapter.

As authors of this document, we used notes and audiotapes from the workshops to inform this presentation of the big ideas. However, because no order for organizing the big ideas was discussed in the workshops, the order used here reflects the authors' best attempts to represent interconnections between big ideas. Each section contains an articulation of the big idea followed by a "clarification" section that describes the scientific ideas underlying the big idea. Following that is an explanation of why each idea is important to nanoscience and nanotechnology. Each big idea section closes with a discussion of how the content might relate to and fit into the current science curriculum.

Big Idea: Size & Scale

Factors relating to size and scale (e.g. size, scale, scaling, shape, proportionality, dimensionality) help describe matter and predict its behavior.

Clarification-

While size defines the nanoscale itself, scale is a critical concept because it defines the set of rules that are needed to explain the behavior of matter at that scale. Size and scale are intrinsically linked. Size is defined as the actual extent, bulk, or amount of something. Scale has several definitions. Scale links the size of an object to a numerical representation of that size in conventionally defined units (e.g., meters, grams, gallons, light years, acres). Properties like size, length, and mass can exhibit large differences in magnitude (Benchmarks). Those large changes in magnitude are often defined as scales, or 'worlds' (e.g., micro-, nano-, atomic-, astronomical). Defining these worlds is important because doing so determines the physical laws that are needed to explain how objects within that world behave. Scale also can link representation to reality. For example, the scale on a map provides a connection between a visual length on the map and a distance in the real world. Scaling links to proportionality and how changes in size are manifested in how a system works.

Not only the size of objects or systems changes with scale, but also the way in which they function or behave also changes with scale. For example, even small changes in linear size yield larger relative changes in area, and even larger changes in volume. Thus, if a property is dependent on volume (e.g., heat capacity, mass), then it will change much faster than properties dependent on area (e.g., cooling surface, absorptivity) for a given change in size. Many of the special properties that matter exhibits on the nanoscale result from the effect of size on the surface area to volume ratio (SA/V). In chemistry, this relates to the number of atoms on the surface relative to that of the bulk material. Because the surface atoms/molecules interact with the environment, SA/V has a significant effect on chemical reactivity. For example, nutrient uptake from the small intestine is more efficient by the millions of projections, or villi, that increase the absorptive surface area. Burning a log is different from burning an equal mass of twigs.

Shape also affects the proportionality between surface area and volume. A 10 x 10 x 10 cm cube will have different properties than a 1 X 10 X 100 cm shape. Both have a volume of 1000 cm^3, but the surface area of the cube is only 27% of the surface area of the other shape. If they were both blocks of ice, under the same conditions, the cube would melt more slowly.

Also related to size and scale is the issue of predictability across scales. Predicting the behavior of a system at one scale does not necessarily translate to behavior at another scale. This presents a challenge in both science and engineering. Moving from a prototype to large-scale production is often a challenging problem in manufacturing. Thus "size and scale" includes concepts not only of size and scale, but also of scaling, ratios and proportions, and shape. In addition, the dimensionality of each of these concepts is also important. Length, area, and volume change disproportionately and thus affect each of these concepts differently.

Size and scale often affect how matter behaves in surprising ways. For example, stars with a mass similar to that of Earth's sun collapse to become white dwarfs and eventually cool down and burn out. However, if the mass of the star is greater than 1.44 times that of the sun, a very different outcome occurs, and the star becomes either a neutron star or a black hole. On the nanoscale, the malleability of copper is derived from movement of clusters of copper atoms on a scale of 50 nanometers. Particles of copper smaller than 50 nanometers lose their malleability and ductility, and are considered super-hard materials. As the size or mass of an object or material approaches the nanoscale, predictions of the behavior of matter begin to fail using classical mechanics. Thus, quantum mechanics must be invoked to explain phenomena on this scale.

Why is this a big idea?

Concepts of size and scale form the cognitive framework that is used in making sense of science in general and in this context, nanoscience. Therefore, these concepts underlie all of the other big ideas of nanoscience. Scientists tend to work in "worlds" that are defined by scale (e.g., astronomical, microscopic). Defining these worlds is important because doing so determines the physical laws that predict how objects within that world behave. As the size or mass of an object or material approaches the nanoscale, predictions of its behavior fail using classical mechanics, which is why the properties of matter on the nanoscale are often unexpected. We make predictions based on our experience, which is on the macroscale (visible with the naked eye) and is the world explained by classical physics. On the nanoscale, quantum mechanics must be invoked to explain the behavior of matter. The forces that dominate the interactions between matter are also dependent on scale. While other forces are present in all interactions, gravity dominates interactions on the macroscale, electric forces dominate at the nano- and atomic scales, and the strong force dominates at the sub-atomic scale.

Throughout history, tools and instruments have been developed to explore worlds that are otherwise inaccessible. The source of this inaccessibility can be due to extremely large sizes like the tremendous distances involved in astronomy, or very small sizes like the inner workings of a biological cell. The tools and instruments make worlds on these scales accessible. Currently, new tools that have rendered the nanoscale world accessible are driving the progress of nanoscale science and engineering. Models and simulations are particularly useful when studying 'inaccessible' systems. They are used to gain understanding, predict behaviors, and explain phenomena as diverse as geological processes, interactions between biological molecules, the history of the universe, and the search for fundamental particles in high-energy physics. With recent improvements in computer technology, more complex systems are now accessible, and it is possible to make better approximations and predictions than ever before.

Fitting it into the curriculum-

Concepts related to size and scale have both mathematical and scientific components and even extend to other disciplines such as geography and history. For this reason, fostering connections among subject areas may support student learning in all areas. In order to communicate the size of things in any subject area, standard measurement units and numerical values are required. The type of units and magnitude depend on the application and the amount of experience that students have. This subject matter tends to fall in the domain of mathematics, but by linking it to science content, student understanding in both disciplines may benefit as one reinforces the other. An understanding of the magnitude of numerical values is necessary before skills at estimating relative quantities and sizes of things can be developed. In history, the timeline is much greater than an individual's life experience. In geography, the scales on maps indicate the size of the representation relative to the real thing. Thus, concepts of size and scale permeate many aspects of the school curriculum.

However, size and scale are not simply academic constructs; they also impact our daily lives. When cooking for a large crowd, cooks scale up the recipe and increase the ingredients proportionally. Travelers use scaling skills to translate the scale on a map to the real distance that they will travel. As students gain experience both in and out of school, they can begin to relate the values and units to the world around them. Because the relative magnitude of these scales is often large, scientific notation becomes a useful means of communicating very large and very small numbers. Implementing this type of notation lends itself to categorizing the size of things by orders of magnitude.

Strong support from mathematics is required before students will be able to apply the concept of surface area to volume ratio to scientific concepts. Students must learn about ratios and proportions, as well as develop an understanding of what area and volume are and how to calculate them. Only after all of that is well understood can students connect that understanding with how SA/V affects properties and behaviors of matter.

Since the nanoscale lies far outside our everyday experience, a robust knowledge of size and scale concepts can be leveraged by students and scientists alike in learning about this intrinsically abstract realm. Developmentally, we first learn about the size of objects intuitively, and in reference to our own bodies. Later we use formal and informal learning experiences to understand the meaning of measurement units, surface area, volume, scientific notation, etcetera. Extrapolating from the everyday world to the nanoscale is probably impossible without using such conceptual tools. Thus, size and scale are the cognitive framework for making sense of the nanoworld.

Big Idea: Structure of Matter

All matter is composed of atoms that are in constant motion. Atoms interact with each other to form molecules. The next higher level of organization involves atoms, molecules or nanoscale structures interacting with each other to form nanoscale assemblies. The arrangement of the building blocks gives a material its properties.

Clarification-

The atomic theory describes a model in which matter is composed of discrete units called atoms. The arrangement of these atoms determines the properties of a material. As the size of a material approaches the nanoscale, the material exhibits novel, often unexpected properties. Nanotechnology exploits these properties to create new materials and devices.

The particle nature of matter is also important because some properties at the nanoscale can be related to properties common to all atoms. Interactions between atoms are determined by their electron configuration thus they are dominated by electrical forces. The principle that the atoms that compose all of matter are in constant, random motion has implications on the nanoscale because the small number of atoms contained in a nanoscale object is sometimes small enough that the motion of an individual atom affects the properties and behaviors of the whole. In addition, electrical forces and thermal motion are essential to the formation and functioning of assemblies.

The specific properties of the constituent atoms are sometimes related to the interesting properties at the nanoscale. For example, a carbon atom can accommodate many bonding patterns. The different ways that carbon atoms bond with each other afford very different materials with very different properties. For example, the bonding pattern (sp2) that is exhibited in carbon nanotubes contributes to the extremely high tensile strength of the material.

Why is this a big idea?

While understanding of the structure and behavior of matter in the bulk and atomic levels is relatively well-developed, limited knowledge exists about how matter behaves as it transitions between the two scales. This region of transition is the nanoscale. Recently developed tools have afforded researchers with unprecedented access to this scale, which is leading to new levels of understanding about the structure and behavior of matter.

Feynman believed that the atomic theory is perhaps the most encompassing aspect of all scientific knowledge. He stated, "All things are made of atoms—little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another." That statement explains much about the structure, properties, and behavior of matter in general. Without having a thorough understanding of these concepts, it is not possible to comprehend the structure and behavior of matter at the nanoscale.

In relation to nanoscience, the atomic nature of matter is also important because some properties at the nanoscale are related to properties common to all atoms. In particular, a) atoms are in constant thermal motion, and b) forces that dominate interactions between atoms are electrical in nature. Both of these properties are essential to the formation and function of nanoscale assemblies.

In addition, some of the interesting properties at the nanoscale can be related to the specific properties of the constituent atoms. An example of this is different forms, or allotropes, of carbon. The most common forms of pure carbon are diamond, graphite and charcoal. In each of these forms, carbon atoms interact differently with each other. Diamond is an extended three-dimensional network, in which every carbon atom interacts with four other carbon atoms. In graphite, each carbon atom bonds to only three other atoms. The most recent models of charcoal suggest a structure that is a combination of these types of interactions.

Other allotropes of carbon are nanoscale structures. Buckministerfullerenes, or 'bucky-balls', are hollow sphere-shaped molecules most commonly consisting of 60 carbon atoms. These structures look much like tiny soccer balls. Structures containing 60, 70, 76 and 84 carbon atoms have been found in minute quantities in nature. Several medically related applications for bucky-balls are currently being investigated. Another allotrope is the carbon nanotube, an extended structure that looks similar to a tube of chicken-wire fencing. Nanotubes have a diameter of only a few nanometers, but extend from micrometers to millimeters in length. As a material, carbon nanotubes exhibit novel properties such as high electrical conductivity and resistance to heat, and are one of the strongest and stiffest materials known. The special properties of carbon atoms afford many different structures, each with its own unique properties.

The basic physics of atoms and molecules is the foundation of all science. Therefore, an early emphasis on these concepts would prove beneficial for students as they study biology, chemistry, physics and earth science. Building understanding in all of these disciplines from the atomic and molecular level will facilitate the interdisciplinary connections that students need to make to understand nanoscience and other emerging science.

How can this fit into the curriculum?

All matter is made up of atoms, but it is the arrangement of those atoms that determines the properties of a material. The electron configuration of an atom determines how it interacts with other atoms thus electrical forces dominate the interactions between atoms. These ideas are currently in the science standards; they provide a critical foundation for understanding the properties and behavior of nanoscale objects and materials. Nanoscale materials themselves are made of atoms, molecules or other nanoscale objects, therefore many of the same principles apply. The same types of electrical forces dominate the interactions as those found between atoms when they form molecules. Likewise, the type of building blocks and their arrangement largely determines the properties of the material.

Consider proteins. Proteins are nanoscale objects that carry out critical functions within all living organisms. It is common for a single building block to affect the structure and function of the whole. The protein hemoglobin, which is the component of the red blood responsible for carrying oxygen, is one example. Hemoglobin consists of four amino acid chains that interact with each other to form a single, functional structure. Amino acids are organized groups of atoms that form the building blocks of proteins. There are two sets of identical chains. One set consists of chains that are 141 amino acids in length (chain A); the other set consists of chains that are 146 amino acids long (chain B). Changing a single, positively charged amino acid, glutamic acid, to the neutral amino acid valine in chain B changes the structure and function of the entire protein. This single change causes sickle cell anemia. The protein maintains its structure and solubility when bound to oxygen. However, when oxygen is removed, due to changes in the way that the altered amino acid interacts with other parts of the protein, the overall structure of the protein changes. The hemoglobin becomes elongated and rigid and polymerizes into long, structured fibers that give the red blood cells a sickle shape (PNAS, 1973). Changing a single building block of the protein changes the structure and function of the whole. Examples such as this make evident that understanding the structure of matter is critical to building an understanding of many other aspects of nanoscience.

Big Idea: Size-Dependent Properties

The properties of matter can change with scale. In particular, as the size of a material approaches the nanoscale, it often exhibits unexpected properties that lead to new functionality.

Clarifying the big idea

Properties are generally defined as those qualities or characteristics that determine the nature of a material. They are the source of the functionality of a material; that is, they determine how it appears, how it behaves, how it interacts with and reacts to the environment, and for what applications it might be useful.

However, while many properties are constant on a given scale, changing the size or shape of a material can lead to changes in its properties. In particular, as the size of a sample decreases and approaches the nanoscale, materials will exhibit different properties that are often unique and unexpected. For instance, spheres of gold with diameters of 1 m, 1cm and 1 mm will all be shiny and gold-colored, and will exhibit metallic properties such as malleability and conductivity. On the macroscale, all of these properties remain the same. However, when spheres of gold become very small, those properties change. On the nanoscale, the color of gold particles becomes very sensitive to size. Gold spheres with a diameter of 13 nm suspended in solution (a colloidal solution) afford a red color. At sizes less than 10 nm, gold loses its metallic properties and is no longer able to conduct electricity.

The source of the unique properties observed on the nanoscale may be either surface- or bulk-related. Surface-dominated behaviors are governed primarily by changes to the surface area-to-volume ratio that occur from changes in size or shape, while bulk-dominated behaviors are related directly to the size or shape of the object or material.

Why is this a 'big idea'?

The unique properties of matter at the nanoscale promise new applications for familiar materials. The fact that properties change with scale is at odds with the traditional concept of "intensive properties" which are defined as independent of the amount of material. However, that definition only applies on the macroscale. As the size of the material gets smaller and approaches the nanoscale, some of those intensive properties do, indeed, change. Therefore, properties can no longer be categorized without qualification as those that do change (extensive) and those that do not (intensive) because all properties can change depending on scale.

The properties that are relevant to nanoscale science include optical, magnetic, mechanical, chemical and electrical characteristics of materials. The nanotechnology revolution revolves around exploiting these properties to solve problems that impact all aspects of society. The cosmetic industry is using nanotechnology to address current concerns regarding sun exposure. For many years, titanium oxide has been used as a sunscreen in the thick white paste that lifeguards use on their faces. More recently, a particulate form was incorporated into suntan lotions. However, dispersions of this form of titanium dioxide left a white film behind, making it an undesirable product. When the particles of titanium dioxide are of nanoscale size, they appear transparent in visible light but still scatter the harmful UV rays. Thus nanotechnology enabled creation of an effective sunscreen that is also a desirable product.

Another optical property to consider is color. Suspensions of gold particles exhibit different colors depending on the particle size. Gold spheres of 10-20 nm suspended in solution afford a red color, while particles 2-5 nm in diameter make a yellow solution, and diameters greater than 20 nm yield a purple color. This technology was exploited as early as the Middle Ages when gold was used to achieve some of the rich red colors used in stained glass. A Roman glass made in approximately 400 A.D. also used nanoscale particles of gold in the process. This glass appears green in reflected light and red when it is lit from within (transmitted light). Nanoscale silver particles also possess interesting optical properties. Suspensions of spherical particles with a diameter of 40 nm give the solution a blue color while 100 nm particles provide a yellow color. Interestingly, changing the shape of the particle also changes the optical properties. Suspensions of 100 nm prism shaped silver particles create a red solution. Other examples of nanoscale optical properties include the iridescence of butterfly wings, opals, and soap bubbles.

The magnetic properties of an object can be size dependent as well. When a magnet is cut into small enough pieces, its magnetic moment becomes increasingly sensitive to the random motion of particles that is always present in matter (also known as thermal energy). At a certain point, the inherent thermal energy of the material is similar to that of the energy required to change the direction of the magnetic moment, which makes the random movement of individual particles significant. This critical size occurs at the nanoscale. Hard-disk drives and data recording tapes are among the applications that depend on magnetic materials. This effect limits the storage density of these products because below this critical size, the magnetic moment of the material is unreliable, which in turn causes information to be lost under these conditions. At the nanoscale, electrical properties are not necessarily the same as they are on the macroscale. Materials that are conductors on the macroscale may lose their conductivity at the nanoscale and vice versa. For instance, when it is thin enough, an insulator can be rendered conductive through a process called quantum tunneling, a non-classical effect that is generally only observed at the nanoscale or smaller.

In addition to physical properties, chemical properties can also change with scale. On the macroscale, gold is considered to be much less catalytically active than other transition metals (Science, 1998). However, nanoscale particles of gold that are less than 8 nm in diameter can act as catalysts to enhance the rate of some chemical reactions. One possible application of this is the catalytic converter in automobiles, in which harmful pollutants like carbon monoxide react to form carbon dioxide and water. The catalysts currently used are only effective at temperatures greater than 200°C (Science, 2004). However, automobiles generate most of their pollution within the first 5 minutes after starting up. Therefore, at the time the majority of the harmful pollutants are generated, the catalytic converter is ineffective due to the low temperature of the exhaust. The application of nanoscale gold particles may help significantly reduce automobile-related air pollution since gold particles catalyze the reaction even at sub-zero temperatures.

The select nanoscale properties discussed above already impact areas as diverse as information storage, electronics, environmental safety, and cosmetics. As scientists and engineers discover and understand more clearly the properties of nanoscale materials, that impact promises to extend to many other arenas.

Fitting into the Curriculum-

Identifying the properties and characteristics of materials is one of the fundamental concepts of science. As such, from their earliest experiences with science, students begin to describe the properties of objects around them. Initially, they rely on properties such as size, shape, color, weight and the material of which it is made. Many of these properties seem unreliable for describing something because they change. For instance, a solid may break into pieces, or an object may be artificially colored. These types of properties are generally designated as extensive properties.

The descriptive problems that are due to properties' changeability are overcome with the introduction of intensive properties such as density, melting point, boiling point and solubility, which do not change and are "independent of the amount of material". The only exception mentioned by these sources is that the individual atoms and molecules do not share the same properties as the bulk substance. These types of properties prove to be useful for comparing different materials and predicting their behavior within the macroscale world. However, as the amount of the bulk material gets smaller and approaches nanoscale size, these "properties that never change" do change. Thus, with the coming of the nanoscience revolution, it is no longer sufficient to teach properties of matter as a dichotomy of bulk, or macroscale, properties versus atomic or molecular properties. Instead, it has become relevant to discuss the properties of matter using more refined levels. No longer can we clearly categorize properties that do change (extensive) from those that do not (intensive), because *all* types of properties can change depending on the scale. The use of intensive and extensive categorization must be linked to scale, as they the terms are meaningful only when describing matter at the macroscale. Characterizing the transition between the macroscale and atomic scale will lead students to a much deeper understanding of matter and how it is put together.

Big Idea: Forces
All interactions can be described by multiple types of forces, but the relative impact of these forces changes with scale. On the nanoscale, a range of electrical forces with varying strengths tends to dominate the interactions between objects.

Clarification-
The behavior of matter can be described by four fundamental forces: gravitational force, electromagnetic force the nuclear force (or strong force), and the weak force. Gravitational force is the dominant force at the macroscale. It describes a force between masses that is always attractive. At the nano- and atomic scales, forces derived from electrical charges dominate. They are a subset of the electromagnetic force, and represent a range of electric forces. Examples of these types of interactions include chemical bonding and intermolecular forces. The nuclear (or strong) force is responsible for keeping the components of atoms together thus is dominant on the sub-atomic scale. The weak force is associated with radioactivity (i.e., beta decay) and other nuclear reactions.

Small objects (e.g., atoms, molecules, nanoparticles) interact in a variety of ways, all of which are dominated by forces that are electrical in nature. These electrical forces create a continuum of forces that predominantly describe all interactions within matter on that scale, the strength of which depends on the entities involved. Historically, these forces are divided into discrete categories: Ionic bonding and interactions, metallic bonding, covalent bonding, hydrogen bonding, van der Waals forces, and covalent bonding. While these categories facilitate communication, none of them exist in pure form.

Ionic interactions occur between ions that have opposite charge of an integer value. An example of this type of interaction is ionic bonding, which involves interactions that are based on electrostatic forces between two oppositely charged atomic and/or polyatomic ions.

In metallic bonding, electrons are delocalized throughout a lattice of atoms. It involves the attraction between the positively charged metal ions and the delocalized electrons and is responsible for the physical properties of metals such as conductivity, malleability, heat conduction and luster.

Covalent bonds are characterized by the *sharing* of one or more electron *pairs* between atoms. This attraction holds molecules together. This type of bond tends to be used to describe interactions between non-metals that have similar electronegativities. These bonds can occur within individual molecules (e.g., H_2O, O_2), and within covalent network solids (e.g., diamond, quartz).

Hydrogen bonds occur between very specific types of atoms or molecules. They consist of an interaction between two partial charges of opposite polarity. Hydrogen bonds generally occur between hydrogen atoms attached to an oxygen, nitrogen or fluorine atom, which gives the hydrogen atoms a partial positive charge. The hydrogen atom will interact with an atom that has a lone pair of electrons in its outer shell and tends to strongly attract electrons when interacting with other atoms (oxygen, nitrogen or fluorine atoms). While other atoms can act as partners in the interaction, the strength of the interaction is significantly diminished. Although they are relatively weak, they can play an important role in the structure and behavior of matter. For example, hydrogen bonding explains many of the special properties exhibited by water. It is also the force that lends specificity to the interaction between the two strands of DNA.

Partial charges are generated by the non-uniform distribution of electrons. This non-uniform distribution can be permanent as in a polar molecule, or induced and non-permanent, the result of time-dependent fluctuations in electron distribution. Attractive forces resulting from this non-uniform distribution of charge are often referred to as van der Waals forces. The permanent dipoles are formed when some atoms of a molecule tend to attract electrons, while others tend to lose them. This creates an uneven distribution of charge resulting in partially positive and negative regions of the molecule, or a dipole. Dipole-dipole interactions occur when the positive region of a molecule interacts with the negative region of another. Under some conditions, the electrons in neutral atoms are displaced momentarily to create a non-uniform distribution of charge and thus induce a dipole. The formation of the induced-dipole, allows atoms to attract each other electrically even though they are neutral. This induced-dipole/induced-dipole interaction is called the London dispersion forces, but is commonly referred to as van der Waals forces. The London forces act on *all* types of atoms and molecules, but increases in strength in proportion to the number of electrons.

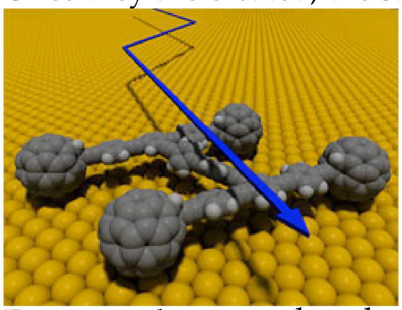
None of these forces exist in a pure form; they always share characteristics of one another. For example, hydrogen bonds have both a dipole-dipole character as well as a covalent character. Thus they actually create a continuum of electric forces, the strength and character of which are defined by the partners involved in the interaction. These forces are not only involved in interactions between atoms and molecules, they also dominate the interactions between objects at the nanoscale. Therefore, it is necessary to have an understanding of all of these forces in order to understand the function and behavior of matter on the nanoscale.

Why is this a big idea?

Nanotechnology exploits the unique properties of matter on the nanoscale to create structures with new functionality. In order to design and build nanoscale structures, it is critical to understand *how* they are structured, which includes how they are held together.

Therefore, it is necessary to have an understanding of the electrical forces that dominate the interactions between the atoms, molecules and nanoscale structures that create nanoscale assemblies and materials.

Electrical forces also have an impact beyond the fabrication of nanoscale structures. Once they are created, the structures are often difficult to manage.



Representation of a nanocar with Bucky-balls (C_{60}) as wheals.

http://www.rice.edu/media/nanocar.html

For example, researchers have built a nanoscale "car" with bucky-balls (C_{60}) as wheels. At room temperature, the electrical forces between the wheels and a gold surface were so strong that the nanocar stuck to the surface. At 200 °C, the car was freed and able to roll across the surface. Therefore, understanding and controlling the electrical forces that can occur between two objects is important not only when building the nanoscale structure, but also when determining the usefulness of the final product.

Because the dominant forces in an interaction are largely determined by scale, the same forces govern many types of interactions. The electric forces that bond atoms together to form molecules are also involved in interactions between nanoscale objects, both natural and fabricated. Biological macromolecules are some of the natural nanoscale objects that fall into this category, including DNA, proteins, and the ribosome. The strength and specificity of the interactions between biological molecules is extremely important as they regulate the biological processes that maintain life. The type of electric force plays a role in the strength and specificity of an interaction. For example, DNA is a negatively charged molecule. During the process of replication, it is necessary to split the double helix into two separate strands. The proteins that are responsible for this function bind primarily through ionic, or electrostatic, interactions between the negatively charged DNA strand and positively charged amino acids on the protein. This interaction is deemed nonspecific because the protein will bind to the DNA in the same manner no matter where it is on the strand. Proteins that bind to DNA with greater specificity regulate the replication process. In this case, the proteins combine ionic interactions with hydrogen bonding to bind to DNA. The limited number of partners that can be involved in hydrogen bonding makes the arrangement of the contacts more important. This increases the specificity of the interaction because the protein must interact with the DNA at a specific location, in a specific configuration, to in order maximize the interactions between them.

How can this fit into the curriculum?

In chemistry, students learn about the bonds that keep molecules together. These bonds are mediated through the electrons of the participating atoms, but are rarely equated in the curriculum to electric forces. Connecting bonds to electrical forces will facilitate student understanding that the same forces are involved in interactions of all kinds on that scale (nano- and atomic). In addition, the curriculum often introduces bonds as categories of interactions (i.e., ionic, dipole-dipole, London dispersion/van der Waals) that involve the attraction between oppositely charged entities. These categories are not discrete because the electrical forces actually form a continuum of forces that dominate the interactions between extremely small objects. Thus, while much of this is typically in a K-12 curriculum, making direct connections between the different types of interactions that are dominated by electric forces involved should solidify the idea that scale determines what type of forces have the greatest impact.

The idea that electrical forces dominate at the nano- and atomic scales includes not only chemical bonding, but also interactions between nanoscale structures both natural (e.g., proteins, DNA) and fabricated. Little, if any, curricular emphasis is typically put on the different electrical forces that are responsible for intermolecular interactions. Shape tends to be presented as the primary determinant of recognition. For example, it is impossible to explain the specificity of the biomolecular interactions that regulate the function of all living organisms only using shape. Rather, the different types of electrical forces primarily control the strength and specificity of interactions.

In addition, while students learn about the different forces that are involved in interactions in biology, they often do not connect those to what they learn in chemistry. For example, the hydrogen bonds that explain the behavior of water should be connected to the hydrogen bonds that keep the strands of DNA together. Too often, students learn the terminology without understanding what it means; therefore, they do not connect the two ideas. Emphasizing this type of connection may help support the concept that the dominant forces on the nanoscale are the same, regardless of the objects participating in the interaction. Currently, there is a movement to change the traditional order of high school science courses (biology, chemistry, physics) such that biology comes later in the sequence. In this way, students will have the foundation to understand the physical basis for the biological functions. These or similar changes may help students make necessary connections between disciplines that are required to understand the concepts and ideas of emerging science, including nanoscience and nanotechnology.

Big Idea: Self-Assembly

Under specific conditions, some materials can spontaneously assemble into organized structures. This process provides a useful means for manipulating matter at the nanoscale.

Clarification-

Recent technological advances not only provide scientists and engineers with the ability to measure and characterize properties of nanoscale materials, but also allow them to control and manipulate matter on the nanoscale. Under certain conditions, matter can even be manipulated atom by atom. One of the biggest challenges scientists currently face is how to do this more efficiently and accurately, which is a requirement for large-scale fabrication of nanoscale materials.

The traditional approach to manufacturing has been top-down, which involves removing pieces of an object in order to reach the final product. This process is similar to creating a sculpture from a block of material. Etching and dissolving are examples in the manufacturing process. However, as the scale gets smaller, it is more difficult to purposefully manipulate matter efficiently, thus creating a need for new approaches to fabrication. An alternate approach is to manufacture from the bottom up, combining smaller building blocks to make larger products. On the nanoscale, these building blocks are atoms and molecules or nanoscale structures, which are brought together such that every atom lies in a precise, designed location. The building blocks can be chosen or designed, and conditions created such that the blocks assemble without further external intervention. This process is called *self-assembly.* Self-assembly provides a means for building nanoscale materials that may possess unique and useful properties. This process is also crucial for applications that require the synthesis of many nano-structures simultaneously.

Although there is consensus on the importance of self-assembly to nanotechnology, the field has yet to develop a unified definition. The following is a general description of the process and requirements of self-assembly. The process of self-assembly involves mobile components that reorient into a structure that is both predictable and organized. In order for this to occur, the components must be in an environment ("certain conditions"), which will induce the desired interaction(s). Once components are introduced into the self-assembly environment, they will organize through attractive or repulsive forces between the components. When objects self-assemble to create stable, bound structures, there must be net attractive forces bringing and holding them together. On the nanoscale, the forces will be electrical in nature. The process of self-assembly occurs spontaneously once certain conditions are set. Thus, the free energy of final state of the *system* is lower than the initial state. Only some materials are capable of self-assembling. They must possess specific characteristics (shape, charge, etc.) in order to be viable. The components of self-assembly retain the physical identity through the self-assembly process and after self-assembly. Therefore, the initial components can be isolated from the assembled structure by providing the right conditions.

While self-assembly is a crucial technique for the advancement of nanotechnology, it is not a new process. Self-assembly occurs in Nature to build structures on every scale. The canonical example would be the process of assembling the DNA double helix, which proceeds with a specificity that has yet to be duplicated by scientists. In addition, some of the molecular machines that carry out crucial functions within all living organisms are built through a process of self-assembly. Thus, self-assembly is a universal concept that engineers have adopted and applied to nanoscale fabrication.

Why is this a big idea?

Nature utilizes self-assembly to synthesize an enormous range of structures from galaxies to biomolecular assemblies on the nanoscale. Perhaps the canonical example of self-assembly is DNA, which is a nanoscale phenomenon since the diameter of the double helix is approximately 2.5 nm. The two strands of DNA come together with a specificity that has yet to be duplicated on this scale. Each strand contains a certain sequence of four bases: Adenine, thymine, guanine and cytosine. The bases each interact with a partner in another strand—adenine with thymine, and guanine with cytosine—to form the double helix structure of DNA. The bases act as a scaffold for atoms (or groups of atoms) that participate in hydrogen bonding. They hold the atoms in a formation that complements the arrangement of the groups of atoms with the opposite polarity that are presented similarly on the opposite strand. Adenine and thymine form two hydrogen bonds when they pair, and guanine and cytosine form three hydrogen bonds upon pairing. The specificity of this simple code is such that a sequence of 16 bases or greater can select its unique, complementary strand from a sequence of DNA that is millions, perhaps billions of bases in length.

Another example of nanoscale self-assembly is the formation of membranes. In this case, the building blocks (e.g., phospholipids) have a hydrophilic end and a hydrophobic end. The hydrophilic end can participate in hydrogen bonding with water, so the interaction with that end is favored over the weaker interactions (dipole-induced dipole) that occur with the hydrophobic end. Therefore in an aqueous environment, the hydrophilic ends all align such that they are exposed to the water and the hydrophobic ends are buried within. In Nature, this process creates the tissues known as biological membranes, an example of which is the cell wall. These membranes are important because they create a barrier that allows cells to maintain different chemical or biochemical environments than those of the outside.

Engineers have adopted the process of self-assembly as a way to overcome the challenging problem of building nanoscale objects with accuracy and precision. The building blocks and the environment are designed such that the blocks assemble themselves without external intervention. This is an example of bottoms-up fabrication. Self-assembly is currently being used to extend the possibilities of synthetic chemistry and to build new nanoscale structures. Chemists combine large, structured groups of atoms that assemble in an ordered, symmetric manner to form ever larger (often snowflake-like) molecules called dendrimers. Synthesis of carbon nanotubes utilizes self-assembly in two ways. The synthesis of the individual nanotubes occurs via self-assembly. Once formed, the nanotubes tend to aggregate through van der Waals forces, aligning to form rope-like structures that are one of the strongest and stiffest materials known. Because of the small scale, bottoms-up fabrication is an important aspect of nanotechnology and promises to play an important role in the efforts to exploit the novel properties of matter on this scale.

How can this fit into the curriculum?

Self-assembly is not just a process used to advance the progress of nanotechnology; nature also uses self-assembly to build structures on every scale. The principles behind self-assembly are the same in both realms in that under certain conditions, objects assemble into an organized structure without external intervention. Thus, self-assembly is a universal concept that engineers have adopted and applied to the problem of nanoscale fabrication.

The process of self-assembly presents an opportunity to build a deeper understanding of the factors that influence the strength and specificity of interactions. In the standards, shape is the primary factor considered to be important for creating favorable interactions. While shape is an undeniable influence on interactions, forces between the objects determine the strength and specificity of the interaction. This concept can be illustrated with shaped magnets. Both shape and polarity will play a role in the final assembly that the pieces adopt.

<insert illustration>

For example, scientists and engineers use DNA to assemble nanoscale structures by exploiting its amazing specificity. In this case, self-assembly can be used to support an understanding of the genetic code and emphasize the tremendous specificity and power that DNA affords.

Big idea: Tools & Instrumentation
Development of new tools and instruments helps drive scientific progress. Recent development of specialized tools has led to new levels of understanding of matter by helping scientists detect, manipulate, isolate, measure, fabricate, and investigate nanoscale matter with unprecedented precision and accuracy.

Clarification-

Technology plays an important role in scientific progress, as science and technology often drive one another. The tools and instruments available to scientists determine what is accessible for them to measure, and scientific hypotheses and theories create a need for new tools and instruments. When new tools and instruments are developed, new worlds become accessible for study. This accessibility leads scientists to new understandings and new questions, which is part of the scientific process.

The degree to which we understand our world is limited, in part, by the tools available to investigate it. Thus, development of tools plays an important part in the progress of science. Telescopes, for example, allow for the exploration of distant portions of the universe, while optical microscopes enable the investigation of a world that is otherwise too small to see. The development of each of these tools led to enormous gains toward understanding the systems within these worlds. Recently tools and instruments (e.g., scanning probe microscopes) have been developed that have rendered the nanoscale world accessible in ways impossible to fathom just a short time ago. These new instruments help scientists characterize nanoscale materials and objects with relative ease and to reveal their special properties. This new accessibility has lead to new understandings of matter on this scale and has aided in the development of new applications.

Why is this a 'big idea'?

Throughout history, the development of new instruments has provided access to previously unseen worlds. Galileo created the telescope and revealed that the Earth is part of a complex planetary system. Today, a variety of telescopes orbit the Earth examining the heavens using not just visible light, but light from the entire electro-magnetic spectrum. The information they gather is providing insight into the formation of the solar system and the Universe itself. Development of new technology has sent probes to distant planets and has even enabled humans to travel through space and explore it themselves.

The field of microscopy has allowed scientists to visualize and explore worlds too small to be seen. In the 17th century, Anton van Leeuwenhoek's optical microscope opened the world of small biological organisms. He discovered that a drop of water was teeming with life and observed that blood was corpuscular in nature. This was the beginning of the biological revolution and lead to a deeper understanding of the structure and function of living organisms. However, the size of objects that optical microscope can visualize is limited to one half the wavelength of the light used for detection. This puts the resolution limit at ~ 0.2 μm when using visible light.

The latter part of the twentieth century saw tremendous advances in microscopy. The scanning electron microscope (SEM) uses a focused beam of electrons to scan a sample and create and image. This technology allows objects on the scale of less than 10 nm to be resolved and has played an important role in the development of nanoscale science and engineering. Scanning probe microscopes are another set of tools for investigating the nanoscale world. Similar to the SEM, this class of tools also creates images by scanning the sample surface, but with a physical probe instead of a beam of electrons. The type of probe determines the type of information that can be obtained. For example, an atomic force microscope (AFM) uses a metal probe that tapers down to a point that has a radius of less than 10 nm. This probe scans the surface of the sample, detecting the interatomic and intermolecular forces between the probe and the surface to create the image. This process is much like using a finger to read Braille. An AFM can measure surfaces with atomic resolution. Other probes can be used to measure other properties of a sample when appropriate, including the size and strength of magnetic features, how well the material conducts heat and the optical properties of a surface. While there are many techniques and instruments that allow scientists to probe nanoscale matter, the type of samples for which these microscopes are optimal and the ease with which they visualize the nanoscale, is a driving force behind the nanotechnology revolution.

Like any instrument, these microscopes have limitations on the type of sample. Because of the nature of biological materials, these tools are not amenable to measuring certain types of information about biological systems. Instead, researchers use a variety of spectroscopic techniques to directly and indirectly probe the structure and function of biological molecules and systems. X-ray crystallography and nuclear magnetic resonance spectroscopy are used to probe the structure and function of a range of objects, from small inorganic molecules to biological molecules and systems.

In addition to visualizing the nanoscale, new tools also provide the ability to create structures on this scale. It is now possible to manipulate matter with a level of control that makes it possible to design and create nanoscale materials. SEMs can be used to create nanoscale patterns on a specially prepared surface. This technology plays an important role in the miniaturization of electronics as engineers work to create micro- and nano-electromechanical devices (MEMS and NEMS respectively). In addition, albeit under extreme conditions, the scanning probe microscopes can be used to move individual atoms into precise positions, affording unprecedented control on the atomic level. Thus, these new tools and instruments are a critical aspect of nanotechnology.

How can this fit into the curriculum?

Much of the grade 7-12 science curriculum requires students to learn about objects and phenomena that are too small to be seen with the naked eye. Beginning in elementary school, students learn about the abstract concept *electricity*. In addition, they are often introduced to atoms and atomic structure. As they learn about living organisms, they study cells and even smaller things that govern the function of the cells (mitochondria, proteins, DNA). Using tools to observe and measure these things that are otherwise not visible may facilitate students' conceptions of such abstract concepts. For example, the change in voltage with resistance is predicted by the equation $V = IR$. Using a voltmeter to observe the effect that changing the resistance in a circuit has in the voltage output provides an experience that may enable students to derive the mathematical equation that explains the phenomenon.

While theory may have predicted the existence of atoms, experimental evidence provided proof of their existence. Unfortunately, the historical experiments themselves are somewhat abstract and may be less than convincing to students. The scanning probe microscopes provide new, more accessible evidence for the existence of atoms. In addition, the images provide evidence for the arrangement of atoms in a solid.
The tools that are available determine what scientists are able to observe and measure. In the past, a need for a new tool was created by the desire to observe or measure a predicted phenomenon. Thus for scientists, developing new tools or instruments is often part of the experimental design. Therefore, this relationship between development of tools and addressing a hypothesis is a key part of the scientific process.

Big idea: Models & Simulations
Because nanoscale objects and phenomena are, by their very nature, too small to see, models are needed to understand, visualize, predict, hypothesize, explain, and interpret data about them.

Clarification-
Models are simplified representations of objects or systems. Some aspects of a given model are the same as the target, but others are necessarily different. Models are essential in all fields of science, helping researchers test and build their understanding of both the natural and fabricated world. Throughout history, the design and manipulation of models have been essential for the advancement of science. Models are particularly useful for making predictions about and working with objects or systems that are otherwise inaccessible. In the case of the nanoscale, the source of this inaccessibility is the size of the structures and systems. The processes that govern the workings of the human body, micro- and nanoscale electronics, drug discovery and medical research, and the creation of highly designed and functional nanoscale materials all involve nanoscale phenomena. Progress in the understanding of these and other areas of nanoscale science has benefited from and depended on the application of modeling. For example, to aid in the design and optimization of potential drugs, pharmaceutical companies create models of structures and systems that are potential drug targets. The use of models has contributed greatly to the scientific progress in these and other areas of nanoscience and nanotechnology.

Modeling is a critical tool for scientists. Models allow scientists to visualize aspects of objects and phenomena, to predict behaviors that can then be tested by experiment, and to organize observations and representations of data. Likewise, modeling has always played a crucial role in the design process. Many nanoscale structures that occur in nature perform functions efficiently under extremely accurate control. These structures have inspired scientists and engineers to design counterparts that duplicate nature's control and efficiency, but can be applied toward obtaining different, desirable functions. Modeling the structure and function of these natural structures plays an important role in the design of the new nanoscale assemblies.

Why is this a big idea?

Much of the science that affects people's lives is not only extremely complex, but lies at a scale too small to be seen (e.g., biotechnology, nanotechnology). Models not only provide a way for scientists to make progress in these fields, but also to facilitate communication among themselves, as well as with the public at large.

Scientists need models to visualize objects and phenomena, to predict behaviors that can then be tested by experiment, and to organize the observation and representation of data. Modeling plays a critical role in nanoscience and nanotechnology research including fundamental studies of the processes that govern the workings of the human body, the micro- and nano-sized electronics, drug discovery and medical research, and the creation of highly designed and functional nano-related materials. Recent advances in computer technology have greatly facilitated modeling and model building of complex structures and systems. With greater computing power comes faster calculations which in turn results in better approximations and better predictions of more complex systems. Thus, as modeling becomes a more powerful tool, the need for developing this skill becomes greater.

Building and refining models are important aspects of the scientific process. This is true even in applied science. Pharmaceutical companies model biological molecules and systems in order to gain insight into their function and the way they work. They use this information during the process of drug development, which includes rounds of design, synthesis and modification. Engineers and scientists use models of Nature's nanoscale structures for other applications as well. Many of the nanoscale structures developed in Nature perform functions efficiently under extremely accurate control (e.g., enzymes, regulatory proteins). Models of these nanoscale structures have inspired scientists and engineers to design counterparts that duplicate Nature's control and efficiency, but perform different, desired functions. Modeling plays an important role in the understanding and design of these new structures. In general, it has played a large part in the progress of nanoscience and nanotechnology and will continue to do so in the future.

How can this fit into the curriculum?

Many have argued that the process of building and refining models lies at the core of the scientific process (Gilbert, Van Driel). Indeed, the National Science Education Standards emphasize that all students should understand that " scientists formulate and test their explanations of nature using observation, experiments and theoretical and mathematical models" (NRC, 1996, p. 171). Likewise, Benchmarks identified models as a common theme, and suggests that their application is critical in fields as diverse as mathematics, education, law, business and finance, science and technology (AAAS, 1993). Hodson names three goals of science education: to learn science, learn about science and learn to do science (Justi, 2005). Thus, understanding, building and using models should be a focus of science education.

Because students often have difficulty in relating models to the reality, gaining this skill in any context will help them make the connections with nanoscience concepts. This skill is critical for learning nanoscience concepts because the nanoscale is inherently inaccessible.

Big idea: Nano & Society

The field of nanotechnology is driven by the aim to advance broad societal goals. As with other technological advances, the products of nanotechnology may impact our lives in both positive and negative ways.

Clarification-

The many interrelationships between science, technology, and the global economy impact society in important ways. Economics and policy can drive science, as was the case with President John F. Kennedy's challenge to put a man on the moon by the end of the 1960's. Much funding and focused effort in science and technology were directed toward meeting this goal. Many of the scientific and engineering advances that were developed to meet that challenge found applications that impacted the greater society (e.g., electronic communications, computer technology, materials development).

The aim to advance broad societal goals such as improved healthcare, increased productivity, and sustainable resources, is a major factor driving the nanotechnology revolution (Roco, 2003). But, the advancement of nanotechnology does not depend solely on successful research and development; an array of societal factors including the education and preparation of skilled workers and researchers, state and federal policies, and economic demands are also contributing factors (Roco, 2003). Thus there is a complex interdependent relationship between society and the advancement of nanotechnology.

Nanotechnology promises to affect our quality of life because new nanoscale applications are being developed to solve problems as diverse as water quality, sustainable energy, and improved healthcare. While these goals are positive, any technological advance carries with it the risk of negative impacts, as well. For example, nanoscale objects are small enough to permeate the biological barriers that protect all living organisms. This means that nanoscale materials present different health risks than the same material at a larger scale. It becomes important then to direct research toward the potential risks as well as the potential benefits of nanotechnology.

Why is it a big idea?

From the discovery of fire and the wheel, science and technology have been employed to improve our quality of life. The Industrial Revolution shifted an economy driven by manual labor and agriculture to one dominated by industry and mechanization. Thus, it changed not only technological conditions, but socioeconomic ones as well. More recently, computers have revolutionized the way people work and communicate, and the Internet has equalized the accessibility of information.

Nanotechnology promises to have a similarly broad effect on society. Already, it impacts applications as diverse as data storage, electronics, and cosmetics, and promises to improve healthcare and the sustainability of agriculture, energy, and the environment. For example, although enough energy from the sun hits the earth every day to meet all energy needs on the planet, we have not yet found an adequate way to harness it. Changing to solar energy from nonrenewable, polluting fossil fuels would have tremendous impact on both environmental and energy concerns. Chemists are developing a nanotechnology application to produce a material that directly converts light to electricity by means of an array of nanoscale solar cells. The cells might be incorporated into a material that could cover a surface like plastic wrap or paint. In this way, nanoscale solar cells could be integrated with other building materials, and could offer the promise of inexpensive production costs that could finally make solar power a widely used alternative to electricity.

In terms of potentially negative consequences, science is frequently ahead of society's ability to deal with it. For example, scientists' ability to split the atom to control nuclear fission changed the world. This technology led to the development of a weapon of mass destruction used to end WWII. From that moment forward, scientists have focused on controlling the use and proliferation of such technology. Currently, nuclear energy accounts for approximately 20 percent of U.S. energy production. While it is clean source of energy that it does not contribute to air pollution, the nuclear waste created by the process poses a problem that will have to be dealt with for generations. Likewise, in addition to new understandings and treatments of human disease, biotechnology also brought with it ethical questions about practices such as cloning.

Nanotechnology promises to raise similar questions. Nanoscale structures are small enough to cross the biological barriers that inherently protect all living organisms. For example, pure gold is inert in its bulk form and has long been used for a variety of applications, including filling cavities in human teeth. Although exposure to gold in this form is not harmful, we do not know what effect nanoscale particles of gold have on our biological tissues in the long term. Likewise, large particles of zinc oxide have been used for decades as a sunscreen. They are FDA approved as an ingredient in this form and for this application. However, the nanoscale particles of zinc oxide that are currently being incorporated in sunscreens and cosmetics have not yet been evaluated. It is clear that they provide effective protection from the harmful UV light from the sun, but we do not know what happens when people are exposed to nanoscale particles of the material.

Part of the process of science is how the new knowledge is applied to solve the problems of current society. In order for the population to evaluate and make educated decisions about new technology, it is necessary to have some level of understanding of the science behind it. Thus, with the extent to which nanoscale science and engineering promise to impact all aspects of society, it is important to create a population that is nanoscience literate.

How can this fit into the curriculum?

We are now in the early part of what may be called the nanotechnology revolution. Nanoscale science and engineering are "science-in-the-making" and can be used to illustrate the dynamic nature of science to students. Doing so provides a way to model the process of science, in contrast with the static, content-driven way that science is traditionally taught in grades 7-12. Students can witness the processes that scientists use when confronted with new phenomena. They can see how engineers use their understandings to create new applications that address various problems and limitations, and students can participate in the debate on the usefulness and the cost-benefit ratio of these applications to society.

Student motivation, interest, and engagement are important aspects for student learning in science education. Positive student attitudes toward science have been correlated to higher performance on science assessments for the majority of students (Neathery, 1997). Eccles and Wigfield (2002) have shown that "interest is more strongly related to indicators of deep-level learning than to surface-level learning" (p. 7), which may explain why students with low interest in science perform poorly on exams that measure deep understanding. Based on previous research, we know that student achievement increases significantly when the science subject matter is relevant to their own lives (Schwartz-Bloom & Halpin, 2003). Participating in the dynamic nature of science and the interplay between scientific discoveries and new technologies with the greater society illustrates that science is not just some knowledge to collect, but an integral part of our lives both present and future. This presents an opportunity to use nanoscience and technology to help motivate students to learn both NSE and more traditional science.

Because of the broad impact that science and technology have on society, study does not need to be limited to the science classroom. For example, when the telescope was invented by Lippershey, it was heralded as a revolutionary new tool for the military, allowing the Dutch fleet to track the movements of the enemy from a great distance. Within a few years, Galileo began landmark studies that changed the way that we look at ourselves within the Universe. In a very short time, a single scientific development had profound impact on diverse aspects of society. Thus, in addition to science class, this discovery has a place in social studies for both its contribution to military strategy as well as the cultural (e.g. religious) implications that Galileo's work had on society.

Likewise, nanotechnology promises to affect many aspects of society. Researchers are developing nanoscale applications to solve problems in areas as diverse as, but not limited to, medicine, sustainable energy and building materials. Efficiently harnessing the sun's energy would impact the world's energy and environmental problems and would thus have a place in an ecology unit or social studies class. The fact that it is a chemical application makes it also appropriate in chemistry. The interdisciplinary nature of nanoscience allows it to fit into many different and presents an opportunity to make connections between disciplines.

Big idea: Quantum Mechanics**

All matter is simultaneously both a particle and a wave. At the scale at which the bulk properties of matter are important, quantum mechanics is not needed to explain the behavior of matter. As the size or mass of an object becomes smaller and approaches the nanoscale, the wave character becomes more important, and quantum mechanics becomes necessary to explain its behavior.

*** As this big idea is relatively new, we are still in the progress of developing all of the supporting ideas. We welcome comments and suggestions.***

Clarification-

Classical mechanics has its foundation in Newton's Laws of Motion. It is a model used to describe the motion of objects in the macroscopic world. This includes things that are visible to the naked eye such as cars, watches, and bullets as well as astronomical objects such as planets and galaxies. However, as the size or mass of an object or material approaches the nanoscale, predictions of the behavior of matter begin to fail using classical mechanics. At this point, quantum mechanics must be invoked to explain the behavior of matter.

Why is it a big idea?

The principles of quantum mechanics are needed in all aspects of nanoscience and nanotechnology. Classical mechanics cannot reliably predict the behavior of matter on the nanoscale, so quantum mechanics must be applied to explain the novel properties of materials that are being exploited by nanotechnology. In addition, the tools that have been developed to help explore the nanoscale world also require quantum mechanics to explain their function.

Quantum dots are nanoscale semiconductors that range in size from 2-100+ nanometers in diameter. Their small size gives them special electrical and optical properties. Like atoms, quantum dots have quantized energy spectra. The color of a quantum dot is related to its energy levels. In particular, the intensity and energy of light emitted from the quantum dot is inversely proportional to its size. Their special properties have potential applications as diverse as diode lasers, amplifiers and biological sensors. Quantum dots also have an extremely high quantum yield—the efficiency with which absorbed light produces some effect. This high quantum yield makes them potential candidates for more efficient solar cells.

An important quantum mechanical effect is tunneling, which occurs when an object transitions through a classically-forbidden energy state. An illustration of this might be pushing a ball up a hill. If not provided with enough energy, it cannot roll over the hill to the other side. However, on the scale when the wave character of particles becomes more important, it is possible for a particle to "tunnel through" to the other side of the potential energy "hill." While the probability of this occurring on any scale is never zero, on the nanoscale it is observed more frequently because the wave behavior of an object becomes more important when its size or mass gets very small. This phenomenon is exploited in one of the important tools of nanoscience, the scanning tunneling microscope (STM). STMs are non-optical microscopes that work by scanning a sharp electrical tip across the surface. The tip is so sharp that a single atom lies at the end. If the tip is brought close enough to the surface, the electron clouds of the atom on the tip interacts with those of the surface. When a voltage is applied through the tip, electrons may jump from the tip to the surface creating a weak electrical current as a result of quantum tunneling, even though the voltage is insufficient to achieve this effect according to the classical model. In order for this to occur, the sample surface must be conductive or semi-conductive. The strength of the current is related to the distance from the surface, which allows the instrument to map the surface of a conductive or semiconductive material. The STM creates images of surfaces to a 2 Å (0.2 nm) resolution, which is the size of some types of individual atoms.

This tunneling phenomenon is also exploited in many electronic applications.
Flash memory is computer memory that can be electrically erased and reprogrammed. It is currently used in digital cameras, cell phones, digital music players and USB flash drives.

Fitting it into the curriculum-
Quantum mechanics is an extremely complex subject that requires extensive experience in both mathematics and science as prerequisites. Its counter-intuitive predictions, borne out in innumerable experiments and applications, are difficult to assimilate even for expert scientists. As such, it is inappropriate to introduce it into the grade 7-12 science curriculum. However, it is reasonable for students to begin to understand the limitations of classical mechanics and how size and scale relate to those limitations. This meta-level reasoning about the affordances and limitations of models is in accordance with current science education standards (references). Other high school level curricular topics can also involve this type of analysis of models, for instance, free fall with and without factoring in air resistance, or ideal and real gas laws. This meta-level examination of modeling would prepare students for the other sets of rules besides classical mechanics that can be used to explain the behavior of the world around us.