(2005, October). Draft, comments welcome.

REPORT OF THE WORKSHOP

SCIENCE AND TECHNOLOGY EDUCATION AT THE NANOSCALE

Acknowledgments

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EXECUTIVE SUMMARY

This document presents the findings of a workshop held to discuss conceptual issues and needs related to integrating the science and technology of the nanoscale into science education.[1]. The workshop, which was funded by the National Science Foundation as part of a *Nanosense* award,[2] was held at SRI International in Menlo Park, California on March 2830, 2005.

The primary purpose of the workshop was to bring together a wide variety of participants, as listed in Appendix A, including educational researchers and science educators (spanning high school, community college, and university levels), nanoscientists, science museum and informal learning specialists, and workforce development staff —to discuss and better understand the impact of nanoscience on education and to plan for the integration of concepts of the nanoscale with science education. In particular, we expected to achieve the following goals:

- Identify representations of core nanoscale concepts.
- Explore the role of hands-on and simulation-based experiences.
- Discuss how to prepare teachers.
- Identify and document industry needs, career paths, and pathways.
- Recommend needs and directions for nanoscale education research.

We intend to use the findings of the workshop to plan for further work by the organizers, the participants, and other interested educators. This report puts forward a coherent series of considerations that bear on the development of materials, software, and activities whose aim is learning—not only awareness—of nanoscience. Additional workshop materials, listed in the Table of Contents and referenced in the text, can be found on the workshop web site available at http://nanosense.org/workshops.html.

Importance of Considering the Nanoscale

Research at the nanoscale both depends on and influences advances in physics, chemistry, biology, material science, engineering, medicine, and technology. Nanoscience and nanotechnology advances have had a significant qualitative impact on science, and have become one of the federal government's top R&D priorities.

Consideration of nanoscience brings an interdisciplinary approach to core issues and concepts from physics, chemistry, biology, materials science, and engineering. The ability to manipulate matter at the scale of molecular, metallic and ionic aggregates, within living or manmade materials, focuses attention on a domain of nature where the predominant models of physics are not the same as they are at the microscopic or atomic scales. The pervasive accessibility of significant computational power introduces the ability to experiment with different representations of reality and to explore their limits and applications based on current scientific knowledge. As a consequence, the problems of interest to science have become more

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[1] Note on nomenclature. Since the terms nanoscience and nanotechnology are often used in confusing ways, we will use the following nomenclature: *nanoscale* will refer to the complex of scientific phenomena and technological applications at the nanoscales of length and time; *nanoscience* will refer to the multidisciplinary studies at the same scale, and *nanotechnology* will refer to the applications of nanoscience.

[2] IMD 0426319.

interdisciplinary and complex, as have the mathematical simulations used to explore and illustrate the unobservable behavior of the smallest particles of matter. The boundaries between traditional disciplines of science—physics, chemistry, and biology—disappear when characterizing or describing the behavior of matter at the nanoscale. Nature, whether within living or nonliving systems, operates by one set of laws. It is important, therefore, to recognize that the models that best describe the behavior of nanosized particles do not differ between disciplines.

The artificial barriers between the classrooms of biology, chemistry, and physics fragment students' conceptions of science and limit their ability to make scientific connections in terms of underlying commonalities, which derive for the most part from molecular or other small aggregate interactions. There is an urgent need, therefore, to reexamine science and technology education to respond to the challenge of educating for a nanoscience future[3]. Computational models adapted from nanoscience research can be powerful tools for science education, but to be effective, these tools must be placed into the proper educational context. The practical implications of these statements will be discussed in the body of the report.

And, we know that, in considering the educational implications of an interdisciplinary science at the nanoscale, we can inform the reform of science education at large.

Workshop Organization

The workshop took place over a three-day period. Prior to the workshop, participants were asked to complete a 10-question online survey, see Appendix B. The results of the survey were used to focus small-group work at the meeting. Representatives from the organizing institutions gave their perspectives on nanotechnology innovations, nanoscience education, and collaborations to support the development of a new nanoscience certificate program and internships for students participating in the program. Presentations included a report on the pre-workshop survey, a summary of FHDA's Atlas of Nanotechnology, refer to Appendix C effort to build a topic map for the domain of nanoscience, and background information on careers in nanotechnology. The small-group discussions focused on four core topics: nanoscience concepts, hands-on experiences in nanoscience, pathways and careers in nanotechnology, and approaches to teacher professional development. Towards the end of the working sessions, each of the small groups summarized their findings and presented these in a whole-group format. The workshop concluded with an afternoon writing session that included several of the workshop participants and organizers who laid the foundation for this report.

It should be noted that the meeting dealt with high school, community college, and lower division college education. We will clarify the educational level of the recommendations and considerations offered in the text.

The report consists of an *Executive Summary*, followed by the body of the report, organized around *When to Teach Nanoscience* and *How to Teach anoscience*, culled from the different working group reports are provided in the Appendices, and also can be found at the NanoSense Web site, http://nanosense.org/workshops.html.

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[3] FHDA's *Atlas of Nanotechnology* (described later) offers the possibility of clear linkages to disciplinary topics and to other scientific concepts, along the lines of the Project 2061 *Atlas of Scientific Literacy*, but goes beyond it in pointing to more detailed learning needs and goals. For more information go to the American Association for the Advancement of Science (AAAS) Web site, http://www.project2061.org/publications/atlas/default.htm.

Findings

> As our mental eye penetrates into smaller and smaller distances and shorter and shorter times, we find nature behaving so entirely differently from what we observe in visible and palpable bodies of our surroundings that no model shaped after our large-scale experiences can ever be true.
>
> Schrödinger, E. (1952). *Science and Humanism*.
> Cambridge: University Press

Schrödinger's quotation refers to the conceptual change in our understanding of nature brought about by the use of quantum mechanics to describe and explore the workings of atoms and molecules. Advances in the science and technology of the nanoscale present similar challenges for both science education and our conceptual understanding of matter. The problem is conceptual and practical; objects and concepts at the nanoscale are *hard to visualize, difficult to describe, abstract*, and their *relationships to the observable world can be counterintuitive*.

This problem suggests the need to reify and model a continuum of scales that can represent non-observable nature in ways that help students integrate their views of matter across scales rather than consider the nanoscale in isolation. The workshop thus primarily considered issues of the integration of nanoscale concepts into science education. This report presents options and strategies for focusing on conceptual learning of core nanoscale concepts within this context. Our goal was science education in general, not nanotechnology education in particular.

Epistemological issues

Some central epistemological ideas identified in our discussions illustrate why understanding science at the nanoscale requires a different educational approach. These ideas can be demonstrated at different scales, and so can be introduced and reinforced in traditional disciplinary courses. Two examples of such ideas are (1) small quantitative changes in some property can aggregate towards large qualitative differences, and (2) matter can be considered as either individual particles, as small groups of particles, or as large group of particles, each with potentially unique properties and scientific and mathematical models and theories.

> It should be clear to students that the behavior and dominance of general laws of physics depends upon the scales of time and distance in which a particular phenomenon takes place, and that scientists determine which laws to apply depending on the scale of the phenomenon.

Learning objectives

Many nanotechnology education projects emphasize size as the lone characteristic of the nanoscale, and isolate it from a more nuanced view of what makes the nanoscale so important. This is compounded by the fact that in many precollege activities, the nanoscale is dealt with perfunctorily. As in all other scientific areas, consideration of multiple critical variables is more effective, leads to deeper understanding, and increases the likelihood of connections to other scientific knowledge. Developing connections to other scientific concepts leads to a broader comprehension of the whole scope of science. These connections are important to developing a sense of context in which to ground disciplinary knowledge. Such integration is critical in the nanoscale.

Four areas whose values vary with scale must be considered simultaneously when incorporating the differences between matter at the nanoscale and matter at the micro/macro scale. How each of the areas listed below is affected when one of the others takes values consistent with the nanoscale allows a more coherent and profound understanding of what leads to the practical applications of the nanoscale:

- *Size*. Macro, micro, nano, and atomic objects.
- *Force*. Gravitational, electromagnetic, weak nuclear forces and strong nuclear forces.
- *Properties*. Mass, volume, surface area, density, charge, as well as thermal, optical, and electrical properties.
- *Time*. Eons, years, minutes, seconds, tenth of seconds, nanoseconds, and picoseconds.

More specifically, the workshop discussion groups listed several topics central to an understanding of nanotechnology. Although all of the topics should be considered crucial to an understanding of the nanoscale in the context of science, the depth at which each of these topics is discussed should vary by education level and more specific learning goals. We are exploring the possibility of developing specific learning goals based on these topics. These topics, around which learning goals can be constructed, include:

- The role of scale in all variables (e.g., size, number, forces, properties, time).
- The role of energy (e.g., interparticle interactions, scale of energy and power).
- The relation between structure and properties (e.g., nanotubes, colloids, thin films, quantum dots).
- Physical properties (particularly surface chemistry effects that dominate at the surface-to-volume ratios found at the nanoscale as well as those properties whose value no longer have meaning at that scale, such as boiling temperature).
- Dimensionality (e.g., scale in one, two, or three dimensions and how characteristic properties of the nanoscale change with dimensionality).

Social implications and relation to the nature of science

A discussion of the social implications of nanotechnology as part of any exposure to nanoscience is important to give students tools that put in perspective the significant publicity, positive as well as negative, found in most public discussions of the topic. Limiting education to show-and-tell awareness demonstrations could build the hype without providing the underlying context, whether that hype extols nanotechnology's potential or decries its dangers.

Another aspect of the social implications for developing nanotechnology is learning to consider the unpredicted consequences of the use of new products. This would involve thinking about environmental, health, and potential social consequences of a new product. Nanotechnology products produce unique concerns and potential problems in these areas.

Consideration of the difference between positive and negative hype could provide a powerful and motivating argument for discussing the nature of scientific reasoning and evidence in general, and could be part of social science or humanities studies taught jointly with science.

Disciplinary basis of nanoscience

At least half of the participants in the workshop felt that nanoscience should be taught in an interdisciplinary fashion, but that practical concerns may dictate integration into disciplinary courses. This section considers such integration.

Participants generally agreed, in the current curriculum, the core sciences most relevant to understanding the importance of large variations in scale are physics and chemistry. The role of scale in biology (as opposed to biochemistry or biophysics) has idiosyncratic characteristics that we did not address, though it was generally acknowledged that within the living cell, nature provides a perfectly elaborated and highly evolved model of how nanomanufacturing occurs.

It is thus most important that physics and chemistry courses bring up a discussion of scale, and perhaps of the properties of the nanoscale at some level of detail, since they can do so in a smooth manner. Other sciences, in particular biology, that deal with particles in the nanoscale range could highlight other core nanoscale concepts (for example, protein self-assembly and molecular fabrication) whenever appropriate.

It should be remembered that science preparation for teachers often takes place in community colleges or in lower division college courses, and that the connections, or lack thereof, between disciplines that these teachers will be able to make in the future will depend on the views of science acquired in these courses. Teacher education devoted to nanotechnology is unlikely to happen in the near future, so it is incumbent upon those teaching science courses for teachers to lay the groundwork.

Our conjecture is that integration across sciences—using the nanoscale as a prompt to highlight fundamental science concepts, given its necessary display of the interrelated features of those concepts, will result in better science understanding by teachers, particularly by those that often are called to teach outside their areas of expertise.

Visualizing and understanding the nanoscale

There is no conclusive evidence of conceptual science learning during the existing nanotechnology show-and-tell activities at all levels. Given the intuitive disconnect between the macro nature of objects used in such demonstrations and the nanoscale of the phenomena, misconceptions may arise. Evidence of learning, with both positive and negative effects, would have significant implications for education funding and practice; we are all proceeding in the absence of such knowledge.

It is also important to clarify which core nanoscience concepts in the curriculum lack successful example laboratories, activities, or demonstrations, so that attention can be directed towards their development. This task requires resources not available during the workshop.

As stated before, objects and concepts at the nanoscale are hard to visualize, difficult to describe, abstract, and their relationships to the observable world can be counterintuitive. When helping students understand the role of scale in science, participants felt that the use of analogies involving scale may confuse students as much as it may help them; analogies should be evaluated before their use for the scientific misconceptions may they generate.

In general, student intuitions based on macroscale experiences can lead easily to the wrong conclusions for the nanoscale.[4] It is imperative that the experiences relate to multiple scales and that connections to properties be highlighted and reinforced repeatedly. Simple demonstrations, such as placing large objects in stations that “increase” by a power of 10, do not lead to the expected understanding of what is important in the nanoscale. On the other hand, “powers of ten” videos are popular. There are several Web sites devoted to their use in education.

Good formative assessment of learning in this domain would be welcome. The group felt that students would benefit from visualizations of scale (not only nanoscale, but atomic and micro scale as well) based on models and simulations depicting matter aggregates that fall below the visible range. And, as will be discussed later, the group agreed that the relationship between structure and function could be addressed more effectively by focusing on properties as a function of scale*,* rather than scale by itself.

Experiential activities and their importance

The workshop participants felt that it is important to have students experience nanoscience phenomena, (see Appendix D for more information), rather than depend only on analogies to help students develop intuitions about scale. Furthermore, it is important to design activities so that phenomena are under student control, rather than under instructor control. The ability for students to verify what an instructor shows or tells them is critical.

One suggested model for laboratory exercises would have students use a remote scanning tunneling microscope (STM) to make a sample, and have other students use a remote atomic force microscope (AFM) to verify and measure the sample. In this way, students would address not only issues of scale, but also scientific issues of repeatability and validation of results.

Open questions on teaching nanoscience

We present some questions raised by participants for consideration in designing nanoscale curricula and learning modules:

- What levels of understanding about nanoscience are reasonable to expect of students within each identified learning contexts, such as high school chemistry.
- Where is the appropriate placement of nanoscience curriculum within each of the traditional disciplines and in high school, community college, and undergraduate science?
- What is the most effective method to produce, disseminate, and offer support for nanoscience curriculum?
- How much theory do you need to teach to reach a certain level of conceptual understanding?

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[4] For example in chemistry learning, Gabel (1998) suggests that one of the ‘complexities’ of learning chemistry is that observations of chemical phenomena are often made on the macroscopic level, yet explanations that students are expected to understand depend on a much smaller, unobservable level. See also Bunce & Gabel (2002) and Nakhleh (1992) for problems students have in understanding the behavior of atoms and molecules.

- How should one balance theory with experiential activities at different levels of education?
- How much (and in what sense) does authenticity matter for learning?
- What leads to better student understanding: demonstrating individual concepts or incorporating them into one realistic example?

Preparing the instructional workforce

Currently, nanotechnology topics are usually limited to examples and sidebars in high school and lower division course science textbooks. The textbook "vignette" model[5] of current topics in textbooks often leaves these topics out of chapter summaries or assessments, leading instructors to ignore them or assign them as optional topics only, which is unlikely to provide students with an understanding of science at the nanoscale.

K-12 faculty in particular still lack the knowledge needed to provide an adequate introduction to concepts at the nanoscale. Even those that do have requisite knowledge generally lack adequate resources for laboratory and lecture materials. Helping teachers reach a balance between motivational show-and-tell activities and conceptual science learning needs to be driven by the development of achievable learning goals.

How do we prepare teachers to teach nanoscience? One approach favored by workshop participants was to support the development of a professional teaching community focused on nanotechnology topics and activities modeled after Silicon Valley biotechnology teaching programs and consortia such as Access Excellence, Gene Connection, and the Santa Clara County Biotechnology Education Partnership (SCCBEP). These consortia include extensive local networks of teachers and provide packaged hands-on units on key topics and authentic techniques. Another example of teacher support community is the Drexel Math Forum (http://mathforum.org) that connects education and mathematics researchers as well as teachers.

SCCBEP is a volunteer organization (http://www.babec.org/SCCBEP/index.html) whose mission is to improve high school science education. It provides access to biotechnology curriculum, supporting laboratory equipment, and technical resources. Its activities follow many of the research-based insights on teacher support, including networking and support for teachers, professional development, mobile kits of biotechnology equipment, and materials allowing students to do laboratory investigations within individualized student projects. In addition, SCCBEP sponsors a program teaming local scientists with classroom teachers, provides teachers with curriculum and training at summer workshops, and has organized community-wide public education events. The partnership has developed its own curriculum and entered into a license agreement with a company, Bio-Rad (http://www.bio-rad.com), for the development of a biotechnology kit.

Preparing the technical workforce

The importance of multidisciplinary education is evident when examining the challenge of displaced workers in electronics and engineering who attempt to enter bioinformatics without a strong foundation in biology and genetics. Educational pathways for nanotechnology learning should necessarily include an opportunity for people with minimal or partial science preparation

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[5] For example, see Brown, Lemay, and Bursten. (2004). *Chemistry: The Central Science* (9th Edition). [place], Prentice Hall

to become aware of nanotechnology and its importance. These learners should initially receive a gentle introduction to the basic principles of the nanoscale, and should continue with remedial basic science learning to facilitate understanding of more specific topics.

One possible approach for introducing nanoscience to people who work in technology and to community college faculty is to create a self-contained and interactive Computer Based Training (CBT) CD ROM. This disc could introduce basic principles of nanotechnology and cover remedial topics in fields such as chemistry, physics, engineering, and materials science. In a similar vein, faculty could develop an open source repository of learning objects (e.g., employing use of the Institute of Electrical and Electronic Engineers (IEEE) Learning Objects Metadata (LOM) and Sharable Content Object Reference Model, SCORM, industry metadata standards) and use a Knowledge, Skills and Abilities (KSA) schema for learning outcomes. Taxonomize, a company that provides information management for learning activities, (http://taxonomize.com), has been working with FHDA on developing a schema for knowledge, starting with nanotechnology for educational use. This schema incorporates domain concepts, curricular factors (goals, sequencing), assessments (outcomes, measures), and presentations (lesson plans, integrating metaphors). The immediate goal was an organized corpus of knowledge to support the FHDA “Introduction to Nanotechnology” course for Fall 2005, with a longer-term goal of creating a formal schema that organizes knowledge for open-source knowledge development. This schema is currently being completed and refined around the corpus of nanotechnology education, culminating in a report on the research results to be sent to NSF in December.

Workshop one-year programs may consider establishing an interdisciplinary minor in areas that incorporate nanoscience concepts. For instance, materials engineering might include chemistry or computer science as minor, and biology, biochemistry, and chemistry might include informatics or computer science as a minor.

As a result of this NSF sponsored workshop, a small group at FHDA, working with the Center of Excellence (COE) at West Valley College and the California Employment Development Department (EDD), will develop one or more survey instruments to determine what industries are using nanoscience and engineering in their products and what typical job titles are associated with that work.

INTRODUCTION

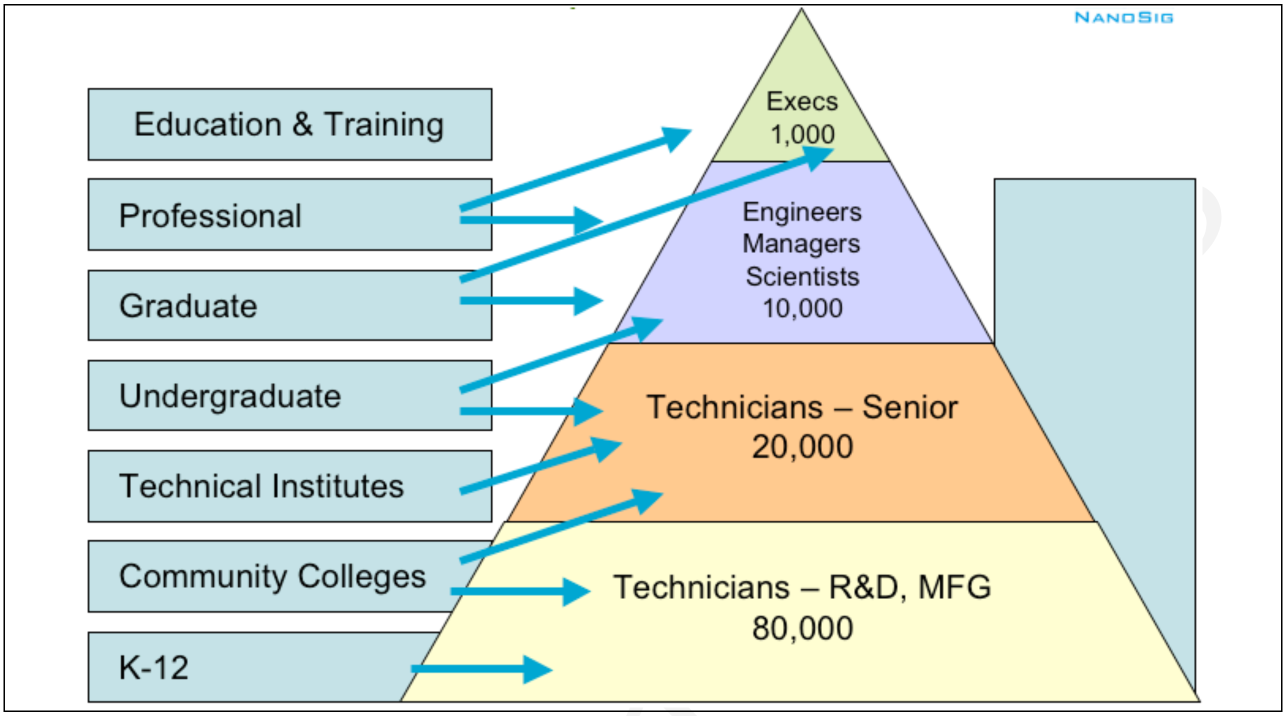
Technological advances made during the last decades have had a significant qualitative impact on science. Two of these advances, molecular-scale manipulation and assembly and computational modeling, have led to a different view of the relationships between scientific disciplines, including mathematics. The ability to manipulate matter at the scale of molecular, metallic, and ionic aggregates, within living or manmade materials, focuses attention on a domain of nature where the dominant models of physics are not the same as at the microscopic or atomic scales, as will be discussed later. The pervasive accessibility of significant computational power introduces the ability to experiment with models of reality and to explore their limits and applications on the basis of current scientific knowledge. As a consequence, the problems of interest to science have become more complex, and mathematical simulations are being used to illustrate the unobservable behavior of the smallest particles of matter. The learning of science can now be uncoupled from the learning of mathematics—and both the mathematics and the science that citizens have to learn will benefit from the broader approach of complex, multidisciplinary educational perspectives. The traditional disciplines of science—physics, chemistry and biology— blur their boundaries when characterizing or describing the behavior of matter at the nanoscale. Nature, whether within living or nonliving systems, operates by one set of laws. It is important, therefore, to recognize that the models that best describe the behavior of nanosized particles are coherent across disciplines.

The practical changes to diverse fields brought by the ability to manipulate matter at the nanoscale—including in medicine, industry, and environmental management—requires a commensurate response from the educational community if we are to prepare responsible and scientific literate citizens. To achieve a widespread scientific literacy that includes the nanoscale, it is necessary to integrate concepts now presented independently in the study of different disciplines, with profound implications for science education. The relevant (or dominant) laws of physics differ according to the scale of the objects involved. Consequently, the study of physics should highlight the scale at which different laws are applicable. Discussions of temperature, for example, could emphasize the meaning of temperature for a molecule vs. an aggregate of molecules. Such integration can be expected to contribute to a more grounded and less hyperbolic consideration of the leading edge of science and technology.

In addition, even if the need for nanotechnology workers is currently small, it is expected to grow significantly in the near future, and can be expected to generate jobs at different skill levels. Although these positions will require knowledge of nanotechnology concepts and skills, the job titles themselves rarely include the “nano” prefix. Figure 1 shows the projected need for nanotechnology workers in the San Francisco Bay Area over the next decade (NanoSIG, 2005). Nationwide, nanotechnology may account for a trillion-dollar annual market and employ two million people within 10 to 15 years, according to an NSF report (Roco & Bainbridge, 2001).

The National Nanotechnology Initiative (NNI; NSTC/NSET, 2005) aims to address such concerns by simultaneously supporting the development of world-class research and education programs and resources to achieve the full potential of nanotechnology, including a skilled workforce and the supporting infrastructure and tools to advance nanotechnology.

Figure 1. Projected Nanoscience workforce development and job generation over the next decade in the San Francisco Bay Area



Source: NanoSig.org

While numerous nanoscale science and engineering education programs exist at the community college and lower division college levels, there is a need for a more focused understanding of how to develop *conceptual* nanoscience knowledge to increase students' scientific literacy and to prepare them for further technology study. Few community colleges or four-year colleges offering nanotechnology courses have the internal capacity to cover the field completely, and they are necessarily opportunistic in their approach. Furthermore, there is interest in bringing nanoscience and nanotechnology awareness, if not education, into high schools and to the public at large.

There is an urgent need, therefore, to reexamine aspects of science education to address the challenges posed by phenomena at the nanoscale, and a parallel opportunity to use the questions raised at the nanoscale range to reexamine fundamental science education issues. Making the science curriculum more nano-friendly could help make much needed improvements in science education in general.

We believe that an effective strategy for integrating nanoscience into science education, particularly but not exclusively in K-12 education, is to integrate the pedagogical knowledge of the science education research and teaching community with the content knowledge of the researchers and educators whose expertise lies in nanoscale research. We have learned much about the importance of multiple representations, open classroom discussions and teamwork for learning complex scientific concepts. We have learned much also about the type of knowledge that teachers must have to guide their students' learning. The education community has validated research-based principles to guide teaching and learning, which, together with the content knowledge of science experts, can lead to effective quality learning for all.

K-12 Science Education Standards and Nanoscale

No discussion of K-12 science education can ignore the relationship of the content it promotes to the science education standards— national or local. Relating concepts to the standards points to the sequence of knowledge acquisition that allows for effective learning. The workshop considered the standards but did not have the time required to make more than cursory connections. A separate NanoSIG meeting at SRI's Center for Technology in Learning (CTL) with high school teachers considered the physics, biology, and mathematics standards in relation to the nanoscale. These connections do not have the backing of a consensus of experts, and others are in a position to deal with the issue in a more principled manner. We thus limit ourselves in this report to indicating some connections between core nanoscale concepts and existing science education standards that exist, and that can be used to justify their incorporation into the curriculum.[6][7][7]

WORKSHOP GOALS, STRUCTURE, AND ACTIVITIES

The primary purpose of the workshop was to bring together a wide variety of participants to better understand the impact and plan for the integration of concepts of the nanoscale into science education. In particular, we expected to achieve the following goals:

- Identify representations of core nanoscale concepts.
- Explore the role of hands-on and simulation-based experiences.
- Discuss how to prepare teachers.
- Identify and document industry needs, career paths, and pathways.
- Recommend needs and directions for nanoscale education research.

We felt that it was important to integrate the knowledge of the science education research community with that of nanoscientists and educators, and to provide sufficient time for in-depth discussions that blend knowledge of science with knowledge of practice. Thus, the number of

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[6] For example the Web site from http://ced.ncsu.edu/nanoscale/scale.htm lists the following, from *Benchmarks for Science Literacy*: What students should know by the end of:
Grade 2: Things have very different sizes, weights, ages, and speeds.
Grade 5: Things have limits on how big or small it can be.
Grade 5: The biggest and smallest values are as revealing as the usual value.
Grade 8: Properties that depend on volume change out of proportion to those that depend on area.
Grade 8: As the complexity of a system increases, summaries and typical examples are increasingly important.
Grade 12: Representing large and small numbers in powers of ten makes it easier to think about and compare things.

[7] For example see http://www.nanoed.vt.edu/curriculum2.htm and http://www.engr.ucr.edu/osp/cnse/activities/ for some links between nanoscience concepts and science standards

participants was limited to fifty. This group included educational researchers and science educators (spanning high school, community college, and university levels), nanoscientists, science museum/informal learning specialists, and community college workforce development staff interested in advancing nanoscience education.

This report does not present a full survey of the topics of nanoscience and science education. Rather, it puts forward a coherent series of considerations that bear on the development of materials, software, and activities whose aim is learning, not only awareness of, nanoscience.

Preworkshop Survey

Prior to the meeting, participants were asked to complete a ten-question online survey whose responses were used to drive the small-group work at the meeting. The ten survey questions reflected the goals of the workshop, and can be aggregated as follows:

When to teach nanoscience:

1. In your own words, what do you think nanoscience education should be? Specify the education level that you are most interested in.
2. What knowledge should students have prior to starting a nanoscience program in college?
3. In high school, what concepts should students understand before going into a college nanoscience program?

How to teach nanoscience:

4. Do you think nanoscience is better taught as interdisciplinary, integrated courses or through traditional, discipline-specific courses (i.e., biology, chemistry, physics, and/or math)? If both, which would you emphasize?
5. What foundational concepts from nanoscience do you think are most crucial to teach? For example, scale and energy are often cited. What others can you suggest?
6. What are a few of your favorite examples that illustrate the concepts mentioned in question 3?

Tools to use in teaching nanoscience:

7. What do you think is the role of laboratory experiences and demonstrations in nanoscience education? Can you give a few examples and specify how they contribute to student understanding?
8. What tools, in general (including modeling tools) do you know of or can you recommend that can be adapted for labs or demonstrations?
9. What nanoscience education materials are you aware of that you think are particularly good?
10. In a nanoscience program, what do you see as the balance between academic learning, laboratory training, and on-the-job training?

Perspective of the Organizing Institutions

Representatives of the three institutions that sponsored the workshop gave short presentations about their institution's goals for nanoscience work and/or education. These perspectives summarized the goals that were later reflected in the discussion.

Larry Dubois of SRI International talked about nanotechnology innovations in industry and at SRI. His presentation is included in Appendix E. He characterized challenging questions for nanotechnology education, and thus, for the workshop as follows:

- Because nanotechnology is inherently multidisciplinary, how does it fit into a standard school curriculum?
- Given a curriculum, how do you train teachers to teach nanotechnology?
- Are there macroscopic manifestations of nanoscience and nanotechnology?
- How do you capture the excitement of nanotechnology without the hype?
- How does one answer the question: "Is there a downside to nanotechnology?"
- Is there really a career titled "nanotechnologist"?

Martha Kanter and Bill Patterson of FDHA presented a perspective on nanotechnology education by discussing their college plans in response to FHDA's mission and student population, and their collaborations with other universities and research institutions (such as NASA). Specifically, they discussed the planning for a new nanoscience survey course, and ongoing plans for degree and certificate options.

Meyya Meyyappan of NASA Ames Laboratory described NASA's interest in nanotechnology workforce development, its collaboration with FHDA to support a new nanoscience certificate program, and the internships offered for students to participate in NASA programs. He also described NASA's nanoscience internships for high school students at the NASA Ames Research Center.

Robert Cormia of FHDA presented a summary of FHDA's Atlas of Nanotechnology effort (Appendix C) to build a topic map for the domain of nanoscience, that combines maps of skills and concepts with a curriculum map of courses taught in the San Francisco Bay Area. The Atlas, under development, was used to stimulate discussion, and represents a new paradigm for organizing nanoscience, nanoindustry, and nanoeducation, and was used by FHDA to plan their nanotechnology programs. One final presentation was made by Adolfo Nemirovsky of NanoSIG as background for the Careers group presentation (Appendix F).

FHDA's Atlas of Nanotechnology

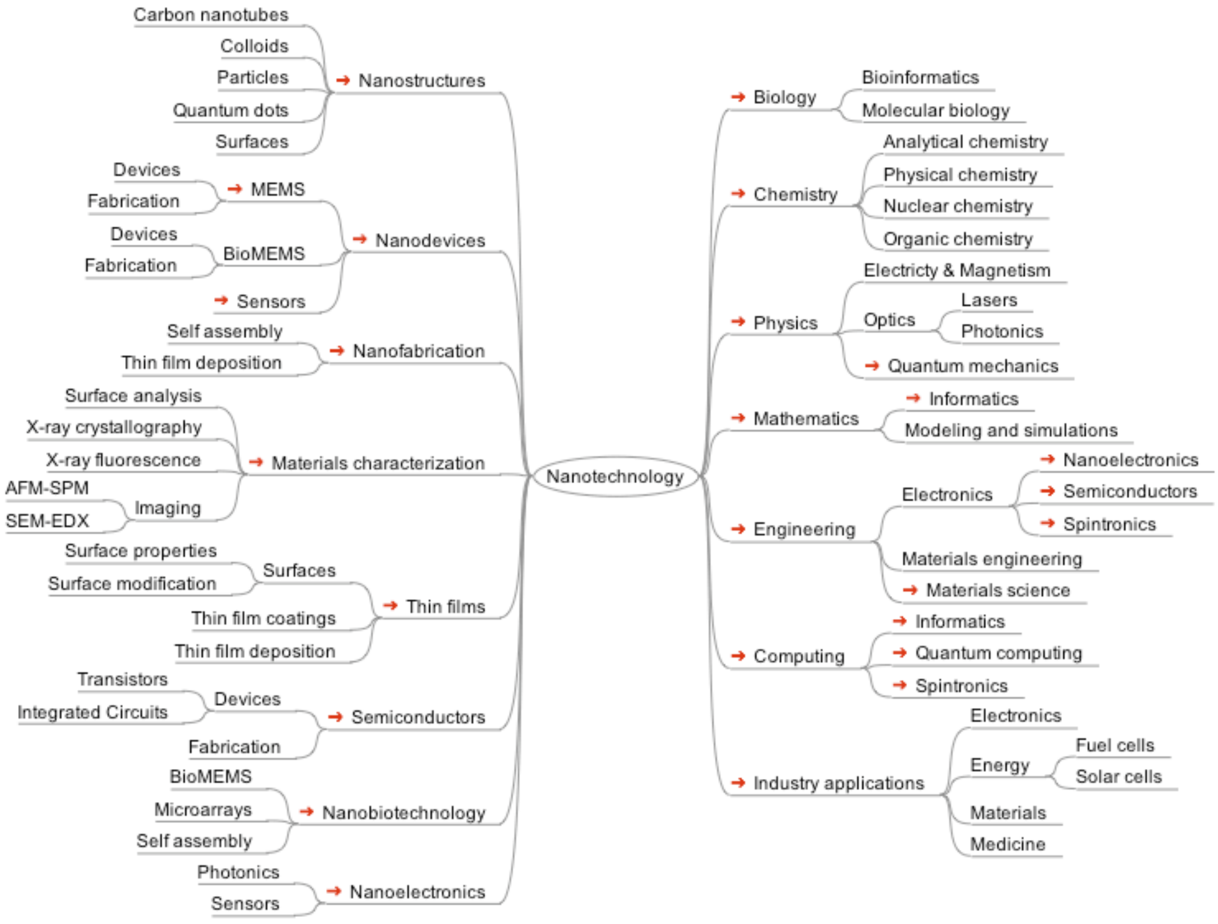
The Atlas of Nanotechnology will link nanoindustry work skills to nanoscience curriculum and training, aiding the intelligent design and management of workforce development efforts. FHDA's first completed topic map attempts to map the entire space of nanotechnology, including both foundational subjects technology-specific areas. Additional topic maps will organize industries, companies, jobs, and, eventually, the work done in nanoscience and nanotechnology. Over 500 courses from local universities will be included in a separate map, with learning outcomes from each course described using a knowledge, skills, and abilities (KSA) data model. Topic maps in the Atlas are interconnected through knowledge and skills attributes, or topic associations, for each node. The goal is to map most key concepts in nanotechnology to a learning outcome in a course or workshop, and likewise, every skill required to work in nanotechnology to a training effort, laboratory exercise, or on-the-job training. Job analysis, as determined from the various industry surveys and environmental scans performed by the Centers for Applied Competitive Technologies (CACT), Center of Excellence (COE) at West Valley College, the California Employment Development Department (EDD), and FHDA will ensure that the maps have identified the critical knowledge and skills for work functions performed in industry. By mapping concept topics and skills to learning outcomes in courses, independent of where those courses might be offered, the Atlas will outline a logical path, culminating in the issuance of a regional certificate. This outline of training will support the development of nanotechnology education and workforce preparation. More details about the Atlas are available in Appendix C.

Workshop Organization

The workshop consisted primarily of small-group working sessions and summary presentations based on these sessions. Two working groups were organized around "concepts"—one focused more on discipline-specific concepts and another focused on emergent concepts. The groups did not focus on explicitly defining learning goals; rather, they concentrated on identifying the concepts critical for an understanding of science at the nanoscale. One group was formed for each of the following topics: experiential (hands-on) activities, careers/pathways, and teacher professional development. Driving questions for each working group included:

- Concepts (survey questions 4—6): What are the foundational concepts from nanoscience and key examples that illustrate them? Should more focus be placed on disciplinary or emergent concepts?
- Hands-On Experience (survey questions 7—9): What is the role of lab experiences and simulations, what are good examples, and how can we best deliver them to students?
- Pathways/Careers (survey questions 1—3 and 10): What are some possible career paths, are there nanotech jobs or just nanoskilled workers, what are industry needs? What are ideal pathway(s) and timeline(s) by which students should be introduced to nanoscience education concepts in K-12, community college, university, and on-the-job training?
- A small group initially discussed approaches to Teacher Professional Development (TPD), and then joined the Concepts and Careers group for most of the meeting, given the overlap between critical topics of both groups. Their discussion on good models for teacher training provided input to the research questions findings, and it is integrated in that section.

Figure 2. Nanotechnology Topic Map



Source: FHDA Atlas of Nanotechnology Project.

FINDINGS

Presentation of the findings are organized around the survey topics: When to teach nanoscience, How to teach nanoscience, and Tools to use in teaching nanoscience are provided in the appendices.

General Considerations

The implications of the new area of nanotechnology for education are challenging. We have to be creative when eliciting understanding about hard to visualize, difficult to describe, abstract concepts. To really communicate the science behind nanotechnology will require a leap in thinking about how best to convey the fundamental conceptual ideas to students in a way that is comprehensible, and using new methodologies that are matched to the cognitive development of the students.

In addition to nanoscale concepts, some epistemological ideas that may help to illustrate the implication of scale were identified in our discussions, such as the idea that small quantitative changes lead to large qualitative differences. Participants agreed that consideration of nanoscale phenomena requires an understanding of the behavior and dominance of general laws of physics at different scales of time and distance, the counterintuitive aspects of the behavior of matter, and the laws and models that describe the behavior of matter outside our normal range of observation. Learning about the nanoscale can highlight these general ideas, and science education in general can benefit from their broader consideration in the curriculum.

Educators must be careful in their approach because science does not fully understand the behavior of matter at this scale, and the expansion of the use of nanomaterials has implications for safety and privacy that are socially relevant and there are no guidelines, as yet, for their use.

When to Teach Nanoscience

The purpose of the concept discussion groups was to identify a critical core of scientific concepts where phenomena at the nanoscale differ from those at the micro or macro scales, and to discuss their possible representations. This identification is critical to map nanoscale concepts to disciplinary courses in high school and college. Although the scientific community does not yet understand all of the behavior that emerges at the nanoscale, some fundamental principles—in particular those related to the differences with the micro and macro scales—are known and can be highlighted in general and introductory courses at the K-12 level, leaving the open questions for consideration by workforce and professional development courses offered by colleges and community colleges.

Core concepts and general principles

There was strong agreement that nanoscience is inherently interdisciplinary. Students would benefit from its inclusion or reference in all or most relevant discipline courses, whether they provide the only opportunity to address the topic or not.

Participants generally agreed that the core sciences basic to nanotechnology are physics and chemistry, and that it is most important that physics and chemistry courses discuss the nanoscale at some level of detail. Other relevant sciences are biology, engineering, and materials science. Inclusion of the nanoscale in biology courses is both feasible and needed, but most likely built around topics such as self-assembly and nanofabrication. Yet, in general, it can be emphasized that the activities that occur within the living cell provide an example from nature of a perfectly elaborated and highly evolved model of how nanomanufacturing occurs, one that we can only hope someday to emulate.

Epistemological considerations, such as that small quantitative changes lead to large qualitative differences, and that matter can be studied as individual particles, a group of particles or a large group of particles, can help lower barriers to understanding why scale is important. Participants agreed that consideration of nanoscale phenomena requires also an understanding of the behavior and dominance of general laws of physics at different scales of time and distance.

The group agreed that a unified approach to nanotechnology education, independent of audience or subject depth, requires addressing simultaneously four aspects of the physical world. These aspects are size, force, properties, and time. As sizes decrease, forces, properties, and time may change may also change.

- *Size*. Macro, micro, nano, and atomic objects.
- *Force*. Gravitational, electromagnetic, weak nuclear and strong nuclear forces.
- *Properties*. Mass, volume, surface area, density, charge, temperature, optical, and electrical properties.
- *Time*. Eons, years, minutes, seconds, tenth of seconds, nanoseconds, and picoseconds.

The group felt that some questions that remain as yet unanswered by science at this time are critical for addressing student learning and cannot be ignored. Many of these questions relate to the transition between scales of matter: When does an object stop being a collection of individual atoms or molecules and become a “material?” How do you characterize a material at nanoscale sizes? If the components are identical when there is a larger aggregate of particles, forming a bulk amount of the same substance, is it the same “material” or not? Is there a rule that aptly describes the transition area between a nanoscale object and a bulk object? Advances in answering these questions would ease the teaching and learning tasks we consider in this report.

The dimensionality, or degrees of freedom, of nanostructures is another general concept that must be addressed directly to avoid misconceptions. A material will have characteristic properties on the nanoscale if its dimensions in one plane are on that scale. For example:

- 1-D (objects confined in one dimensional space, but extended in the other two dimensions). Examples are surface coatings, thin films, device junctions such as diodes, and interfaces. These are the most technologically advanced and well understood. Atomic scale control is possible in this dimension.
- 2-D (objects confined in two dimensional space, but extended in the other dimension). Examples of these structures are nanotubes, fibers, nanowires, and others. The properties of these 2-D systems are not entirely understood and their manufacturing is less advanced.
- 3-D (confined in all three dimensions). Examples of these systems are quantum dots, particles, precipitates, colloids, catalysts and others. These systems present the greatest challenge in terms of defining properties and manufacturing. This is where the increase in surface area to volume ratios is the most dramatic, with a corresponding increase in chemical reactivity.

Another relevant aspect of the science behind nanotechnology is that the models we normally use to think about matter are not fully applicable when applied to the nanoscale. Again, this is a general situation, not specific to nanotechnology. Historically, each time that science has been able to gather qualitatively new data and observations, we have learned more about the laws that govern our natural world. The new generation of scanning probe microscopes has the ability to gather information about materials at the nanoscale that was not possible to collect before. We do not yet know all the patterns that will begin to emerge from its analysis. There have been no new scientific laws discovered at this time, but such a discovery may yet happen.

Given the multiple goals of science education at different levels, ranging from simple awareness of principles to future professional practice, the integration of the nanoscale and its associated curricular areas in education can be viewed on a continuum, from concepts and phenomena that occur solely within the confines of traditional science, engineering, and mathematics courses, to an approach that creates integrated theory and practical courses that bridge traditional disciplines. It should be noted that these approaches can be complementary, not exclusionary. Making conceptual relations clear can go a long way towards a deep understanding of the nanoscale and the avoidance of the hype often associated with nanotechnology.

Workshop discussions focused on characterizing nanoscale phenomena, and how models and modeling can play an important role, recognizing that just one dimension of an object has to be in the nanoscale range for the object to display nanoscale behavior. The influence of local (atomic/molecular) behavior on larger scale systems is a common theme in science. A parallel concept in biology is ecology. It is possible to use simulations to illustrate how this happens. In biology, even simple agent-based models can show how individual interactions between predator, prey, and resources can have implications and subsequent changes for many or all plants and animals living in that environment. Concord Consortium, a nonprofit educational research and development organization, (see http://www.concord.org for more information), has created this type of interactive computer software to help all students learn complex science.

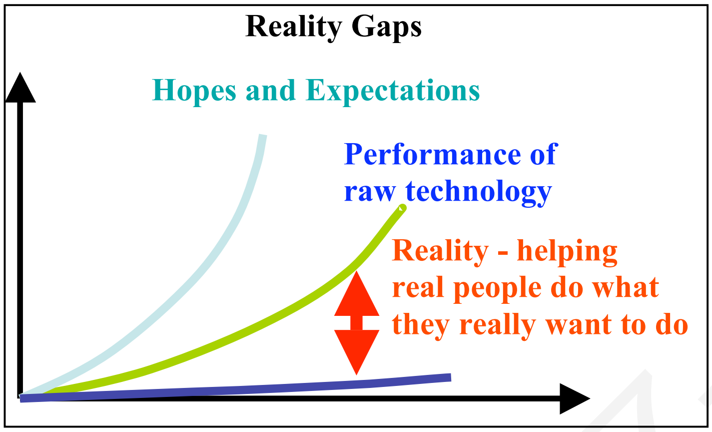
Theoretical considerations

The group raised the question of whether there is a sequence of tractable primitive concepts (akin to DiSessa's p-prims) for nanoscience, and if so, uncovering them would be a worthwhile project. For example, the concept of "stickiness" is highlighted in San Francisco Exploratorium activity that provides a good example of pouring at the small scale. They have a very, very tiny teapot magnified on a screen, and kids can manipulate levers to fill and pour water from the cup, but the water is just a drop so it sticks instead of pouring. "Slime science" is another good activity for uncovering primitive concepts. In this activity, people (who have prior conceptions of solids and liquids) and are given a material that acts like neither a solid nor a liquid. Also discussed were examples of activities that are much more visible, like a grape juice dilution activity—examples where the phenomena is under student control so they can verify what an instructor tells them.

How to Teach Nanoscience

The implications of the new area of nanotechnology for education are challenging. We have to be creative when eliciting understanding about hard to visualize, difficult to describe, abstract concepts. To really communicate the science behind nanotechnology will require a leap in thinking about how better to convey to students the fundamental conceptual ideas in a way that is

Figure 3. Reality gaps in expectations of new technologies



Source: Reality Gaps by Daniel Atkins

comprehensible, and thus require new methodologies that are matched to the cognitive development of the students.

A realistic understanding of the implications of nanotechnology as part of nanoscience education is important. It is therefore useful to prepare students for the hype found in many public discussions on the topic. An example of negative hype is the story of Ice-9 by novelist Vonnegut (1963), which portrays a man who creates a new form of water that has the ability to “solidify” all normal water it comes in contact with. Other examples of what could be misinformed hype include the use of remote “nanosensors” to violate individual privacy, and “nanobots” capable of self-replication that could run amok in the world.

Positive hype also exists, as exemplified in the following statement from “Anatomy of a Nanoprobe:”[8]

> Within a few decades, nanotechnologists predict, they will be creating machines that can do just about anything, as long as it's small. Germ-size robots will not just measure internal vital signs; they will also organize the data with molecular microcomputers and broadcast the results to a mainframe (implanted under your skin, perhaps), where the data can be analyzed for signs of disease. Nanomachines could then be sent to scour the arteries clean of dangerous plaque buildup, or aid the immune system in mopping up stray cancer cells, or even, a la Fantastic Voyage, vaporize blood clots with tiny lasers.

Whether or not this statement eventually proves true, sophistication in estimating its degree of likelihood and reality is required. The same can be said about other futuristic representations.[9]

In fact, the difference between positive and negative hype, the nature of such hype in considering nanotechnology, and students’ interest in “nanobots” could provide a powerful drive for using examples such as these for discussing the nature of scientific reasoning and evidence in general.

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[8] More information about ‘Anatomy of a Nanoprobe’ is available at: http://www.nanotechnow.com/Art_Gallery/joe-lertola.htm.

[9] More information is also available at: http://www.foresight.org/Nanomedicine/Gallery/Captions/.

Each new technology device that is invented needs to take into account the balance between desired and unwanted effects; nanotechnology devices are no different. We need to make clear to students that new revolutionary scientific discoveries have associated social responsibilities. Any technology development will have some level of impact on society. As we are teaching these different disciplinary concepts, ethical issues will need also to be addressed.

As the central science concepts of nanotechnology are integrated into science education, it becomes apparent how disciplines fit into nanoscience relative to each other. The concept discussion groups listed the following concepts as being central to understand nanotechnology. These concepts are typically introduced to students in upper division or graduate classes within specific disciplines. These could be expressed as conceptual learning goals, and could potentially be introduced to students at an earlier stage in their education. We are exploring the possibility of developing them.

1. Role of scale in all variables (e.g., size, number, forces, properties, time).
2. Role of energy (e.g., interparticle interactions, scale of energy and power).
3. Quantum principles and probability (e.g., quantized energy, quantum numbers, Heisenburg's uncertainty principle).
4. Relation between structure and properties (e.g., nanotubes, colloids, thin films, quantum dots).
5. Increased role of surface phenomena in determining properties (e.g., surface chemistry, surface physics, interfaces).
6. Unique form of properties at the nanoscale (e.g., electromagnetic, mechanical, optical) as well as a consideration of those properties whose value no longer have meaning at the scale, such as, boiling temperature.

The following concepts are the province of engineering:

7. Self-assembly of *components* of aggregates, not only aggregates (e.g., bio-nanotechnology, crystal structures).
8. Control of fabrication (e.g., tools, processes, metrology).

In the example of scientific contributions to nanoscience from biology, the group felt that many of the relevant biological examples come down to surface chemistry. In relation to points 4 and 5, we considered drugs or medicines targeting particular enzymes or cell types, as well as diffusion. Capillary action within and among cells is a physical process often described in chemistry courses.

There are many potential nanoscience applications within biology, such as the use of gold particles to cook cancer cells.[10] Where in biology or medicine would we see new applications? Sensors, hazardous materials containment, the determination of the individual genome sequence, the targeting and tailoring of drugs, and directed therapy are just a few of the applications to biology that are current areas of discussion and related research. The more we can solve the mysteries of nanotechnology, the more we can apply that knowledge to our efforts in biology.

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[10] Nanospectra Biosciences has developed gold-coated glass nanoparticles capable of invading a tumor and killing it remotely when heated.

Similar considerations about core concepts can be identified for physics and chemistry (points 1—3) and engineering (6—8). Self-assembly, molecular recognition, and DNA polymerization were seen as a possible examples of surface chemistry.

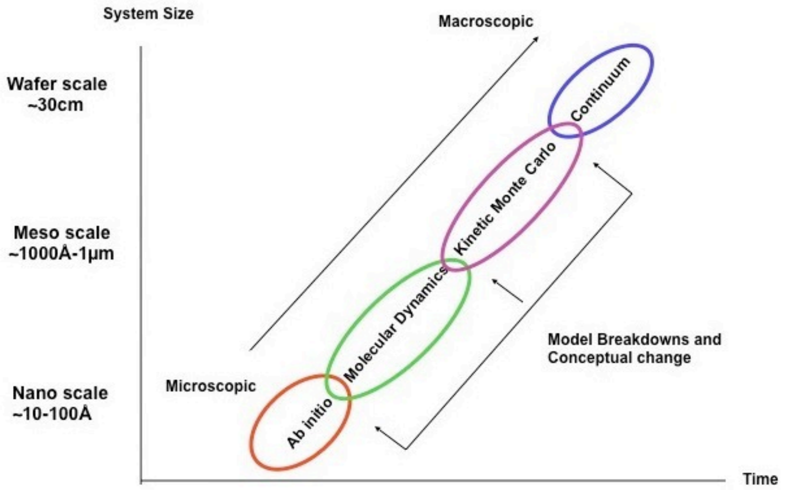
Focusing on how specific observable properties change as the size scale changes may provide students with an easier access point for understanding how different theoretical models represent different parts of the scale. Specifically, our discussions highlighted conductivity and reactivity properties because of their importance in engineering and their strong dependence on particle size. A possible focus on optical properties and conductivity would allow students to explore the dependence of the size of the band gap on the surface-to-volume ratio of particles and the corresponding effects on absorbance and conductivity. A focus on reactivity would allow them to explore the importance of ratios of surface area to volume in catalysis. In both cases, the underlying scientific models can be part of the pedagogical considerations, indicating the conceptual test points where models break down.

> The group noted that all of the concepts listed are central to materials science, and felt that understanding why surface effects dominate (the surface to volume ratios that characterize the nanoscale) was critical for an introduction to the nanoscale. That is, most particles in a bulk material are not on the surface, but particles on the nanoscale have a much larger exposed surface. When the surface-to-volume ratio becomes huge, behavior changes at the surface and edge interfaces. Following the evolution of properties as the surface ratio increases can be an effective way to demystify nanotechnology.

Figure 4 shows the methods that are used to study matter at a range of sizes. Starting from the atomic level, *ab initio* (and semi-empirical) methods approximate the solution to Schrödinger’s wave equation. Molecular Dynamics methods refer to using computational modeling of finite groups of particles (e.g., 1,000 molecules). Tools such as Concord Consortium’s Molecular Workbench employ methods of this type. “Kinetic Monte Carlo” methods refer to using statistical approximation methods for larger groups of particles. The computational engines behind tools such as NetLogo and AgentSheets employ methods based on Monte Carlo.

Our knowledge of behavior of bulk substances comes from observations and data collected at the macro scale. We describe the properties of particles at the atomic scale based on our observations at the macro scale, generally considering aggregations of atoms or molecules such that statistical laws apply. Using properties as the entry point would also provide the opportunity for students to become familiar with tools used to empirically probe the properties of matter.

Figure 4. Characteristic Scales of Simulation Methods and Limits of Different Models



Experiential Activities

The goal of the discussion of hands-on activities was to identify ideal practices and resources, needs and gaps, research questions, and challenges related to possible nanotechnology experiential modeling activities on precollege student learning. Members of the group included college, high school, and informal educators who held a common belief that we would be better served by sharing examples of good activities and laboratories across these contexts. The specific list of activities generated by the group is available in Appendix D. (Note that this list should not be considered exhaustive or taken as a formally evaluated list.)

Recommendations were preceded by consideration of two basics questions: (1) “Why is it important today to teach young students about nanotechnology, and tell eighth graders things that graduate students do not even know?” and (2) “What are we taking out of the curriculum to teach nanotechnology?”

Answers to these questions clarified the objectives of the group: If we do not educate younger students at some level, the mass media will. Anecdotal evidence suggests that younger students are interested in nanotechnology—it is a hook for them and a nice way to provide an interdisciplinary perspective. However, participants agreed that we need to shift some of the resources allocated for nanoscience education into integrating nanoscale concepts with general science education. Definition of what would constitute a good pre-college nanoscale curriculum is much needed, and could help orient some of the show- and-tell activities towards more specific learning. One danger is that is of limiting the education to show-and-tell demonstrations that could build the hype without providing an underlying base on which to judge it.

Participants briefly tackled the relative worth of macro-sized models of nanoscale phenomena, and considered that these activities present the danger of “numbing” theoretical aspects—creating serious misconceptions as to the properties of materials at scales below which observation of features cannot be made. We need to consider whether we can get too hands-on in an introductory setting or whether we are covering the concepts (or theory) needed to enable understanding of the experience.

Participants argued that science education research suggests that the experiential/conceptual basis comes before theoretical and abstract understanding, and the issue should be what experiences are useful and which ones are confusing in this context. It was agreed that experiential activities should be made available to students. Students who can understand abstractions more rapidly may not need as much hands-on experience, but others, with less basic preparation, may need hands-on experiences designed for easy transfer. Using narratives and story-centered curriculum was raised as a possible alternative approach to get kids to ask questions based on a "real" context.

> New properties of matter are becoming apparent when we explore the nanoscale, and we may need new models or significant extensions to existing ones to model these properties. At the nanoscale, properties are changeable under small variations in scale rather than remaining constant as they do at the bulk level.

Another general consideration was introduced by a Lawrence Hall of Science representative, who indicated that the Hall chose to not promote examples that were more than 5—10 years in future because they did not want to fuel the hype aspect of nanotechnology presentations. For example, they do not have an activity describing quantum dots, which have interesting properties, but are highly toxic.

The report of the group's discussion is summarized in the *Ideal Practices and Resources* outline below.

Ideal Practices and Resources

- Authentic, transparent tasks
    - Layer of bubbles
    - Koolaid dilution
    - Lego AFM
    - Pouring tea exhibit
- Use of stories and narratives
    - Mystery of the Sick Puppy (problem-based learning)
    - Goal-based scenarios
    - Movie scripts
- Using simulations and online modeling
    - Virtual AFM
    - Molecular Workbench

Authentic, transparent tasks

Participants had many example tasks and activities and were happy to share them. The first example mentioned involved pouring tomato juice into a pocket of a white shirt coated with NanoTex fabric to show that it does not leak; you can even drink from the pocket with a straw. Another favorite was North Carolina State University (NCSU)'s problem-based learning activity for middle school students, called the Mystery of the Sick Puppy, in which students are told that they have a dog that is sick and they need to conduct a series of experiments to see what virus it has.

Materials Research Science and Engineering Center, University of Wisconsin-Madison, (MRSEC), has created lab activities that illustrate self-assembly with magnets or LEGOs were also recommended. Several participants had used and liked the LEGO AFM model. North Carolina State University, NCSU, has a machine that simulates an AFM using tips connected to an ink pen so that students can see how an AFM works. Others simply had students use a laser pen, move it up and over an object, and trace dots on a board behind it to show the surface outline. The classic black-box activity in which items are placed in a box and students use skewers to "feel" and guess what is inside was also recommended to help students become familiar with using tools to touch and understand things they cannot see. It should be noted that there is not yet conclusive evidence of the learning that takes place or the misconceptions that may arise given the macro nature of the objects used.

The NanoKids activity from Rice University was mentioned, but was not recommended—participants felt that the abstract dancing cartoons did not help students learn nanoscience concepts.

Surface-area-to-volume experiments involving segmented cubes, experiments with different size pieces of ice to illustrate heat loss, and dilution with food coloring were reported as effective. Another activity that reportedly worked well was laying a string across a room, making size marks on it, giving kids a number of cards representing various objects, and asking them to lay the objects down on the string, ordered by size. Children have to argue it out, and the experience interests them.

Use of analogies and narrative

When discussing activities that may help students understand scale, some participants felt that analogies involving scale are liable to confuse students more than help them. Simple demonstrations, for example, placing large versions of objects in a hallway at stations that "increase" by a power of 10, do not seem to lead to the expected understanding. But popular "powers of ten" videos seem to work better, and several Web sites are devoted to them.

Predicting how big a spider would be if its leg was 6-feet long and the classic question about what would Barbie would look like if she were the height of an average woman are exercises that have been used to talk about scale. However, research suggests that if students do not have good math skills, they will not understand scale completely, although they may have some conceptual understanding.

The power of narrative could be used constructively at some levels. A good example is the famous "Flatland" books.[11] One participant gave a "life at low Reynolds number" example of ants in a boat: if they start to row, the water would seem like the consistency of honey to them. Another participant recommended Steven Vogel's book *Life in Moving Fluids.*[12]

Creative writing and story-centered curriculum could be implemented through the use of science fiction. For example, students could read a passage of a popular text (like *Prey*[13]) , and additional reading, considering societal, cultural, and fictional parts of the world around the premise of the book. Research suggests that stories stay in long term memory longer that other texts, although it is important to inform students of the factual and the fictional parts of the stories or book. The popularity and longevity of some classical books speaks to that permanence; the approaches used in *Mr. Tompkins Universe*[14] and in *Alice in Quantum Land*[15], an allegory in quantum physics.

Participants agreed that it takes time for young students to be able to move beyond the size issue. For example, when asked, "What it would be like if you were the size of a nanometer?" several students mentioned that they could crawl under the door and see what is going on next door or that they could get stepped on. In reality, they could not even crawl over the fiber, and it probably would not even matter if they were stepped on!

Activities that involve imagining living in a nano world are hard to understand and may even be counterproductive, particularly at young ages. We note again that our objective is conceptual learning, and that we are not referring here to show-and-tell awareness activities that do not consider conceptual learning.

Using simulations and online modeling

The discussion then turned to the use of demonstrations, laboratories, and real vs. simulated experiences. The Ontario Science Center was commended for its demonstrations of unique properties of materials, such as one involving smart metals that bend in hot water and bend back when removed ("memory wire") and another involving composite materials that do not absorb shock so a ball bearing bounces on it for an extremely long time. The Franklin Institute's demonstration materials were also recommended. Another suggested laboratory exercise has students use a remote STM to make a sample and then has other students use a remote AFM to verify and measure the sample. This approach nicely addresses scientific issues of repeatability and validation of results.

Participants felt that the most difficult concepts to understand fall under the umbrella of quantum effects, and that particularly for these concepts, it is easy to generate misconceptions. Therefore, care should be exercised when deciding the student level at which to introduce quantum effects. Tunneling and qubits (units of quantum information) are two core phenomena at a higher level that make nanoscience quite interesting to young people. In tunneling, an

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[11] Abbott, A. (1884). *Flatland: A romance of many dimensions*, 1884; Dover. For more information see: http://www.alcyone.com/max/lit/flatland/.

[12] Vogel, S. (1996). Life in moving fluids. Princeton, New Jersey: Princeton University Press.

[13] Crichton, M. (2003). Prey. New York, New York: Harper Collins.

[14] Gamow, G., Stannard, R. (2001). The new world of Mr. Tompkins. Cambridge, United Kingdom: Cambridge University Press

[15] Gilmore, R. (1996). Alice in quantum land.. United Kingdom: Sigma Press.

electron can suddenly jump across a gap to be in a new location. The movie "The Incredibles" was mentioned as an apt analogy to use for discussing tunneling. The quibit concept relates to a phenomenon that is understood (but hard to explain) where there are three possible states: on, off, and both on and off at the same time—unlike current computer memories that are on or off but not both. This phenomenon is being studied in the research lab, and could be used to enhance computer memory (e.g., one bit could store 8 states instead of the current 4).

A good demonstration of self-assembly would be particularly useful in an introductory lesson. A possible demonstration was put forward by taking a pump and blowing out soap bubbles, all the same size, into a tub of water. The bubbles will space themselves out on top, in one layer to achieve the lowest energy. This illustrates the concepts of self-assembled mono layers. It also illustrates the concept of low energy states—if you pop a bubble in the middle, all the others will rearrange to remain in the lowest energy state.

Quantum dots was another area in which lab activities were desired. The University of Wisconsin-Madison Materials Research Science and Engineering Center (MRSEC) has an Interdisciplinary Education Group (IEG) group has created a lab activity that demonstrates the unique optical properties of quantum dots. This group uses examples of nanotechnology and advanced materials to explore science and engineering concepts primarily at the college level. They have created many laboratory kits, activities, video instructions for multiple nanolabs, and in general have created a lot of curricular material that can be used for the specific purpose of bringing the excitement and potential of nanotechnology and advanced materials to the public. For more information about the materials and resources this group offers see http://mrsec.wisc.edu/Edetc/index.html.

In discussing the tension between simulated vs. real experience, it was noted that more and more, young people have less direct experience of machines in the real world—through radio building kits, chemistry kits, fixing bicycles, and so on—making it harder for them to distinguish real technology from imagined technology. The vocational component of education has decreased, fewer kids take shop classes, and the computerized motors in cars nowadays are less understandable to the uninitiated. How can you teach students about nanomotors if they do not have a direct experience of how a "normal" motor functions? Giving students real experience is particularly hard for nanoscience: there are quantum phenomena that can not be replicated at the macro level, only simulated. Student intuitions based on macroscale experiences can also lead easily to the wrong conclusions for the nanoscale. When scientists see the connection between macroscale phenomena and nanoscale phenomena, it is imperative that the connections be highlighted and reinforced repeatedly. One participant told an anecdote about how his group had just acquired a new scanning electron microscope, but the young students to whom they showed the generated images said they did not believe that they were real. A student assistant then opened the microscope and showed the children the specimen. When the children saw the samples in addition to the images, they then believed the images were real.

Research questions to assess the impact of hands-on activities

- How much (and in what sense) does authenticity matter for learning?
- How does context change experience?
- Are there clusters of examples that deepen understanding?

- What leads to better understanding: demonstrating individual concepts or incorporating them into one realistic example?
- How do you measure impact in light of Hawthorn-like effects?
- What are the everyday concepts and intuitions (e.g., stickiness, smelliness) that can be leveraged for understanding of nanoscale phenomenon? What is the developmental sequence? How do you assess this?
- What examples of nanoscience can be used to support cognitive conflict?
- How critical is hands-on experience with research tools to learning? (e.g., time with an AFM)
- How should a lab infrastructure be organized to support hands-on experience?
- What types of activities and performance-based assessments are best for nanoscience learners?
- What aspects of lab experience are key to capture/ and replicate in virtual experiments?
- How do you elicit and make explicit students' conceptions of nanoscience?

Problems, needs, and gaps

- Interactions and behaviors that are difficult concepts to understand (e.g., tunneling, quibits, thermal noise, quantum effects, emergent behaviors). Behaviors are different at nano and macro scales, and learner intuitions are misleading.
- There is a tension between reality and fiction; trying not to feed the hype and keeping media informed of actual science.
- New forms of assessment will be needed. These need to be determined how best to integrate and embed compelling assessments into new nano experiences.

Grand challenges

- Understanding the ethical, social, technical, educational context of nanoscience.
- Establishing quality control and criteria for good nano educational learning experiences.
- Understanding when and how to teach nanoscience, at what levels and depths, when to teach concepts within or across disciplines. Identifying the developmental sequence of concepts to learn in nanoscience. Determining what to remove from the curricula to make room for nano concepts.
- Developing tools to communicate nanoscience concepts.
- Balancing the physical and virtual experiences, knowing when and how they work.
- Determining to prepare and support teachers to enact nano materials.

Possible solutions

- Develop and use open source repositories for nano curricula.
- Create an infrastructure for leveraging museum and industry laboratory instruments in larger network of co-labs.
- Conduct annual meetings with nano-educators.
- Create nano apprenticeships for underserved youth, and for new and experienced teachers.

Careers and Educational Pathways

The purpose of the career and pathways group was to document the education needs of different nanotechnology education levels, based on their expected employment needs in Silicon Valley:

- Nanotechnology-oriented certificate
- Professional degree (associate's, bachelor's, doctorate)
- Workforce and professional development (which in this report includes teacher professional development)

The discussion of needs was based on an "80% foundation / 20% specialization" approach (see Fig 5). The presentation addresses the following core issues:

- Clear understanding of work entailed: Where and what are the nanoskills?
- Surveys of nanoskilled workers: How did people get to where they are?
- Certificates vs. programs: What level of knowledge and skills are best for each?

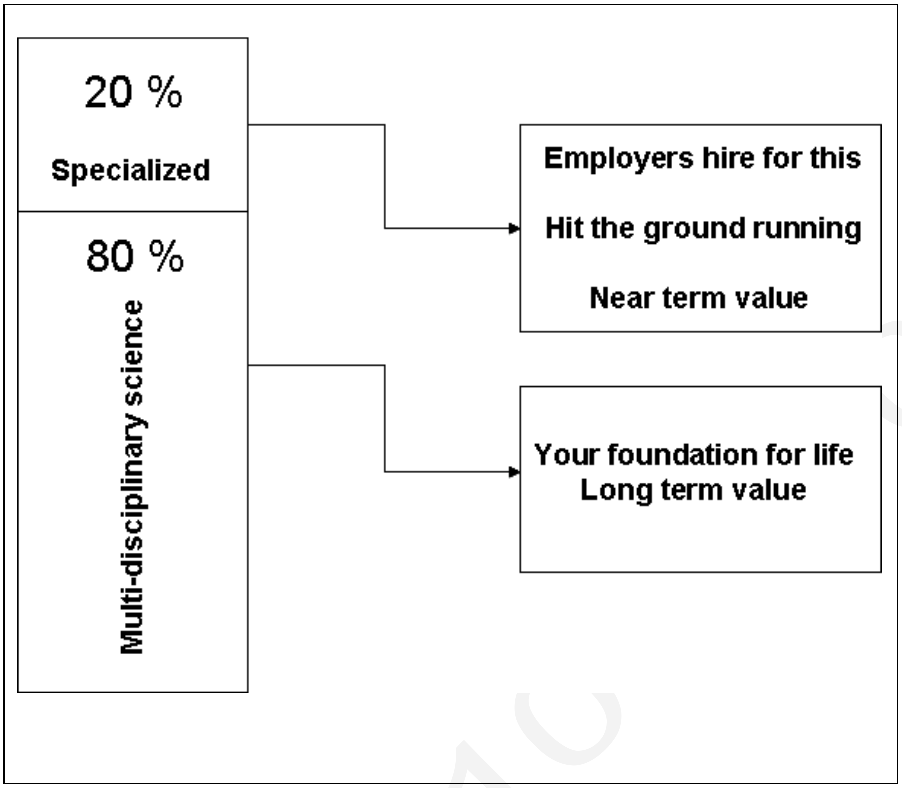
Rather than consider nanotechnology as a monolithic industry, the group thought of individual industries and workers as "nanoskilled;" that is, there are nanoskilled industries and nanoskilled workers in those industries. Nanoskilled careers—implying the need for re-education and career advancement as the science and technology develops—is what we need to prepare students for.

The primary question throughout the session was "How do we prepare people to perform in and understand nanoskilled career opportunities and requirements?" Workforce awareness typically depends on high-technology industry workers having knowledge of nanoscale concepts and skills that allow their industry to design, engineer, and manufacture at that scale.

Keeping skills current is a challenge for the workforce in general, and especially for workers requiring nanoskills, as there are limited training materials and programs other than the rigorous graduate school courses and two- and four-year disciplinary training (materials science, engineering, chemical engineering, and so on.) A career assessment tool focusing on nanotechnology, using industry-accepted terminology of knowledge and skills, would help determine the need for individualized training. Workforce awareness also includes knowledge of key targets of industry, including stem cell and genomic research, emission-free energy, and high-performance materials.

Research activities in other regional centers (such as Albany, New York and Austin, Texas) suggest areas where Silicon Valley needs to be competitive. Gap analysis (along dimensions of knowledge, skills, and abilities) can be performed at the individual, corporate and regional levels. As such, education plans may require customization for individual focus rather than a one-size-fits-all program. A certificate of documented skills and knowledge may also be useful. It is important to understand industry efforts and industry practices required to address the need for a workforce prepared in nanotechnology. Competencies are needed, and defining knowledge and skill attributes of learning outcomes will lead us to these competencies.

Figure 5. Needs of General vs. Specialized Nano Education



Nanotechnology for Dummies CBT

Educational pathways for nanotechnology should necessarily include an opportunity for people with minimal science preparation to become aware of what nanotechnology is, why it is important, with a gentle introduction to the basic principles of the nanoscale dimension. One possible approach is to create a self-contained and interactive CBT that will introduce any person to the basic principles of nanotechnology and covering remedial topics in chemistry, physics, engineering, and materials science, etc.

The proposed CBT would target technicians in high-technology manufacturing, especially electronics, biotech, and materials engineering, and would be a good training source to accompany a 90-day on-the-job training (OJT) program. The CBT could include links to many open-source training tools, and would likely include many onboard multimedia files to explain technical concepts in an easy to visualize format. Self-contained topics could include chemical bonding and molecular geometry, band gap theory, stress and strain, and real-time multimedia rendering of atomic force microscope (AFM) images and scanning probe microscope (SPM) measurements.

Certificates and degrees

Throughout the United States and the world there are hundreds, if not thousands, of courses that touch on some aspect of the nanoscale. These range from materials science, engineering, and chemical engineering to electrical engineering and semiconductors. In the Bay Area alone, there are over 500 courses on the Peninsula and in the South Bay that include Stanford (200+), San Jose State University (100+), UC Santa Cruz (100+), University of Santa Clara (100+) and lower division courses at community colleges including FHDA, City College (San Jose and San Francisco) and Mission College. Major worldwide centers include Penn State, University of Minnesota (Dakota County Technical College), University of New South Wales (UNSW), and Stanford professional development.

A thorough analysis reveals that there is commonality of direction and content in these programs, which range from basic materials science and nanostructures to semiconductor fabrication, nanoelectronics, and nanobiotechnology. FHDA has started a topic map of course content, including a directory of terms and keywords that might be used to approximate a rough sketch of learning outcomes.

It was suggested that faculty develop an open source repository of learning objects using the IEEE Learning Objects Metadata (LOM) and SCORM industry metadata standards and a Knowledge, Skills and Abilities (KSA) schema for learning outcomes. This repository was also described in an NSF proposal, and subsequent work has taken place to connect the nano (terminology) topic, concept, and skill maps with a resource map of learning objects. This is work described further in the Appendix C about the Atlas of Nanotechnology.

Target audiences

Target audience for nanoscience and technology education includes four main sectors:

- K-12 students (pipeline into college)
- Traditional 4-year and graduate education
- Remedial and fast upgrade of skills for the current workforce
- Transitional workforce (displaced workers)

The pipeline of K-12 students should provide an ample supply of students entering traditional science and technology careers. These students will be exposed to some nanoscience and technology in high school, especially the advanced placement (AP) students. While K-12 has been the focus of many nanoscience programs, including some at SRI International, K-12 faculty still lack adequate resources for providing the necessary lab and lecture materials for providing an adequate introduction to concepts at the nanoscale. This is an area where a balance between motivational show-and-tell activities and conceptual science learning needs to be discussed.

Current working professionals seek quick ways to acquire knowledge of the nanoscale, and especially look for remedial and fast skill upgrade, including terminology. These activities tend to be employee driven, rather than industry mandated. When a company realizes knowledge and skills are needed by many workers, traditional professional development and Web-enhanced or online education become a strategic investment and priority.

Traditional four-year programs prepare students for advanced degrees and programs, including graduate programs, with a strong emphasis in materials science, and also for direct entry into the workforce. While these programs provide excellent knowledge and skills, especially engineering and chemistry programs, they often lack good exposure to technology.

The transitional workforce looks for access to immediate training in nanoscience and technology if it can offer the promise of employment. Many workers are in fields that are no longer growing or no longer of interest to them. Nanoscience provides excitement, even discounting its hype. Training stipends and workforce development monies are becoming more available in this sector, especially targeting displaced semiconductor and Internet-technology workers.

Educational paths, as distinct from target audiences, focus on the types of education and training provided. K-12 nanoscience education tends to follow the traditional science curriculum, with the addition of laboratories and exercises that build on properties of the nanoscale, especially as an interdisciplinary science. Web-assisted lessons, especially those that might be part of an open source directory, can be very useful in providing multimedia and other simulations of complex topics. Four-year programs may consider establishing an interdisciplinary minor in nanoscience. For instance, materials engineering might include chemistry or computer science as a minor, and biology, biochemistry, and chemistry might include informatics or computer science as a minor.

Workforce development programs may use a guide like the FHDA Atlas of Technology (skills inventory map) to chart a path towards incremental skill upgrades, including training that might occur in nanocenters, for example, MEMS and semiconductor fabrication, thin film deposition, and fabrication of carbon nanotubes and other novel structures. Transitional workers, especially those with semiconductor experience, might be placed in MEMS, microarray, solar array, fuel cell, or other training programs that can leverage their process experience in silicon.

Nanoskilled careers

Nanoskilled careers comprise work in research, development, and manufacturing where functionalizing and productizing nanoscale properties occurs. Nanoskilled work today includes engineering and design in the semiconductor, biotech, and high- performance materials industry. Typical job titles are design engineer, application engineer, process engineer, and package design engineer, in semiconductors; chemical engineer, plating engineer, organometallic chemist and polymer engineer in applied chemistry; microarray applications engineer in biotech, and materials scientist in the materials industry. Nanoskilled careers require advanced degrees in chemistry, physics, biology and biotechnology, engineering, electronics, materials science, informatics, bioinformatics, and computer science. Additionally, successful and long-lived careers are often built on multiple degrees, as nanotechnology is both interdisciplinary and multidisciplinary.

By sector, semiconductors, including micro-electro-mechanical systems (MEMS), are the largest single provider of nanoskilled jobs, followed by biotechnology (microarrays), and by firms engaging in research and development in high-performance materials application. Additional fields where nanoskilled jobs have high growth include energy, development of solar panels and fuel cells, high-performance materials where carbon nanostructures and alloys are employed, and nanoelectronics where functionalizing quantum properties is critical.

Both the industry survey and industry focus groups, combined with intelligent data mining of the EDD database of existing high-technology jobs, will help define the regions in the high technology sector where nanoskilled careers are likely to occur. (Sample jobs posted at TinyTechJobs, available at http://www.tinytechjobs.com, are shown in Appendix G.)

Industry surveys

Some members of the group, particularly from FHDA, stated that they will need to do an industry survey of both people and firms to determine what skills industry will need, and what education current nanoskilled workers obtained to get where they are, to answer the question: What kind of education do we need to catalyze workforce development to meet future research and development needs? With an understanding of current knowledge and skills in the Northern California region, FHDA may be able to do an aggregate gap analysis determining what we need to supply in training and work experience to keep our workforce competitive.[16]

- The Center of Excellence (COE) at West Valley Community College is planning on using an environmental panel to determine, among other things, the size of the industries requiring nanoskills (number of companies, jobs, and market size) the knowledge and skills need for nanoskilled employees, and if possible, projected growth over the next 5 years.
- Erik Alexander of the FHDA Employment Development Department (EDD) has a large database of jobs with a work and skills inventory, coded by industry, and referencing standard job titles. The EDD database can be mined to reference a general description of job titles that are both appearing in nanoskilled hiring venues, and/or job titles of people in the industries requiring nanoskills to compare it with the EDD job database, and determine (approximately) what skills may be needed to prepare our local workforce to do the kinds of work to produce products at the nanoscale.
- Further collaboration is needed with other colleges and universities that have a nanoscience skills inventory, for example, the University of Minnesota (Dakota County Technical College) which has a fairly thorough inventory of 30 local companies in chemicals, electronics, agriculture, and optics.

A core task in developing effective education and training programs is in mapping work skills to curriculum standards. Using the computer industry technology association (COMP TIA at http://www.comptia) and DACUM (Develop A Curriculum approach to occupational analysis) methods, combined with an industry topic map of competencies,

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[16] Online surveys, targeted towards both industry and individual workers, might help us understand (quickly) what knowledge and skills are required to obtain specific job titles, and further, what knowledge and skills inventory was critical for workers to retain key positions in nanoscience and technology. If we use local industry lists (e.g., IEEE) we could reach upwards of 50,000 persons in Silicon Valley, and using industry lists of company names (slower) we could contact from 500 to 1,000 local companies. The goal would be a survey that reached about 500 to 1,000 employees total, reducing to roughly 50 to 100 job titles. Using a COMP TIA (DACUM) approach, we can build a critical knowledge and skills inventory for tasks associated with the work performed in these job positions.

FHDA and COE will attempt to develop a knowledge and skills inventory for nanoskilled work. This approach is both rigorous and time-consuming, but leads to accurate analysis of job training requirements.

Multidisciplinary foundation and specialized training

The 80:20 rule of foundation knowledge related to specialized training applies to nanoscience and nanotechnology. Most people who have retained employment and built successful careers in nanoskilled industries have a foundation comprising one or more degrees in traditional science and engineering, and often an advanced degree in a field related to their undergraduate work. Those persons with multiple degrees that create a multidisciplinary knowledge and skill base will have best foundation to add highly specialized skills that employers seek. Specialized training such as that for x-ray lithography, DNA microarrays, materials characterization, molecular modeling, and informatics, includes many specialized skills that require a strong knowledge foundation. The importance of a multi-disciplinary education is evident when examining the challenge of displaced workers in electronics and engineering who attempt to enter bioinformatics, but lack a strong foundation in life sciences in general and biology and genetics in particular.

As a result of this NSF-sponsored workshop, a small group at FHDA including COE and EDD will develop one or more survey instruments to determine what industries are working to employ nanoscience and engineering in their products and what typical job titles are associated with that work. Using an "environmental scan," a thorough description of nanoskilled work, including the knowledge and skills required for those jobs, will be developed and will help map work skills to curriculum standards. As FHDA develops a program for both academic and workforce development in nanoscience and technology, we will need to ensure that educators' foundational knowledge in science is sufficient for building a specialized set of training materials and programs to meet the growing needs of industry.