# Developing the Human and Physical Infrastructure for Nanoscale Science and Engineering

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## 1 Vision for the Next Decade

### *1.1 Changes of the Vision over the Last 10 Years*

In 2000, the National Nanotechnology Initiative (NNI) Implementation Plan [1] recognized that nanoscale science and engineering education is vital to U.S. economic development, public welfare, and quality of life. But the Nanotechnology Research Directions report's vision for education and physical infrastructure only

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addressed (a) the need for a multidisciplinary university community based on the unitary concepts in nanoscale science and engineering, and (b) the need to enhance access to fabrication, processing, and characterization equipment ([2], p. 153). As described in Sect. 2, considerable progress has been made toward – and beyond – that early vision.

The importance of improvement in U.S. science, technology, engineering, and mathematics (STEM) education has been highlighted by three recent reports [3–5]. In 2000 the NSF initially focused attention on graduate programs, with goals described as follows: "Educational programs need to be refocused from micro-analysis to nanoscale understanding and creative manipulation of matter at the nanoscale – A 5-year goal – is to ensure that 50% of research institutions' faculty and students have access to a full range of nanoscale research facilities, and student access to education in nanoscale science and engineering is enabled in at least 25% of the research universities" [6]. As the decade progressed, and the growing, pervasive impact of NSE became more compelling, the NSF vision for NSE education evolved (see Fig. 1) to include undergraduate, community college, K–12, and informal venues [8].

NSF and Department of Commerce (DOC) also recognized early on the importance of convergence among the emerging fields of nanotechnology, biotechnology, information technology, and cognition, NBIC [9], and the need to improve education and training to adapt to advances in emerging new technologies.

Nanotechnology is now seen as a driving force for all major industries worldwide and as playing an essential role in solving challenges in areas such as energy, water, environment, health, information management, and security. To compete effectively in world markets, it is now recognized there must be continued attention to NSE discoveries emanating from graduate education, motivated and skilled entrepreneurs who can transition discovery into innovative technologies, state-of-the-art equipment for fabrication and characterization, well-trained workers for the industrial communities, and well-informed, nanotechnology-literate citizens to sustain the workforce pipeline and public support. Attention must be given to expand and sharpen the education efforts in all of these venues.

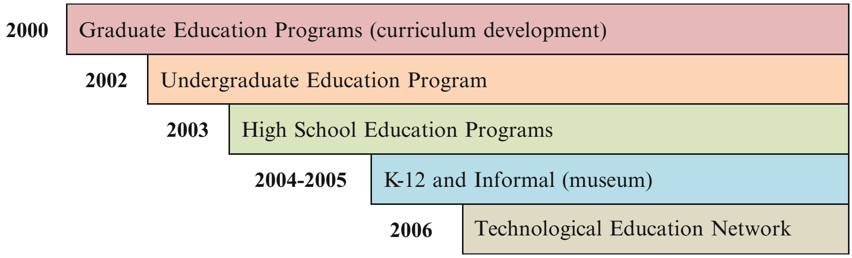

**Fig. 1** Schematic of NSF investment in nanoscale science and engineering education, moving over time to broader and earlier education and training (After Murday [7])

## 1.2 The Vision for the Next 10 Years

The vision for nanoscale education in the coming decade is to build out the nation's human and technical infrastructure better enabling rapid, effective introduction of innovative nanotechnology-enabled products and processes that can address our shared social needs.

To realize this vision it will be necessary to:

- Continue the remarkable progress in science and engineering discovery facilitated by the marriage of research and education
- Sustain and update state-of-the-art fabrication and characterization facilities
- Incorporate new science and engineering knowledge, as appropriate, into the curriculum at all educational levels
- Ensure that the transdisciplinary nature of nanoscale science and engineering is not inhibited by traditional academic disciplinary constraints, but rather enriches and transcends them
- Facilitate the promises engendered by the convergence of nanotechnology, information technology, biotechnology, cognitive and other sciences (NBIC)
- Facilitate nanoscience-enabled innovative solutions to pressing global problems such as energy, water, environment, health, and information processes
- Provide first-rate training and recognition to teachers of K–12 science, technology, engineering, and math (STEM) classes
- Entice students into science and engineering careers
- Develop school-based nanotechnology career clusters that help prepare high school students for careers in nanotechnology
- Develop an informed, skilled workforce
- Include nanotechnology in retraining programs, such as those sponsored by the U.S. Department of Labor
- Enable workers and members of the general public to be sufficiently knowledgeable to understand the benefits and risks of nano-enabled technologies
- Provide adequate nanotechnology student and worker safety training
- Incorporate safety, social, and ethical issues into nanotechnology courses
- Institutionalize proven nanotechnology education programs

In addition, the state-of-the-art laboratory facilities that have been developed over the past 20 years – so critical not only to education, but also to research and technology development – must be provided with adequate operation and maintenance funding to ensure effective access by user communities (including students, small and medium enterprises, and larger-scale industries), be continually updated to sustain state-of-the-art capabilities, and coordinated nationally and globally in cost-sharing partnerships. Most important, those facilities must also be expanded to provide prototyping capabilities that will accelerate the transition of research discoveries into innovative technologies.

# 2 Advances in the Last 10 Years and Current Status

A main goal of the NNI has been to develop the educational resources, skilled workforce, and supporting infrastructure and tools to advance nanotechnology. A solid start has been made towards attaining this goal, but much remains to be done.

## 2.1 *Physical Infrastructure*

Nanoscale R&D user facilities have experienced significant advances in the past decade, both in the United States and around the world. Since 2000, about 100 national centers and networks and about 50 other research organizations focused on advanced R&D have been built or repurposed, together constituting a strong nanotechnology experimental infrastructure in the United States. The National Nanofabrication User Network (NNUN, www.nnun.org), a consortium of five leading university facilities providing nanofabrication user services to the R&D community, was established in 1994 with a focus on extending microelectronics; in 2003, NNUN was effectively morphed and expanded into the National Nanotechnology Infrastructure Network (NNIN; http://www.nnin.org/) with 14 participating sites distributed across the country. It has become an international model. The NNIN provides extensive support in nanoscale fabrication, synthesis, characterization, modeling, design, computation and hands-on training in an open, hands-on environment, available to all qualified users (see Sect. 8.8). The Network for Computational Nanotechnology, with Purdue as lead university, was created in 2002 to design, construct, deploy, and operate a cyber-resource for nanotechnology theory, modeling, and simulation (see Sect. 8.4). In the 2007–2008 time frame, large instrumentation user facilities were opened by the Department of Energy (DOE; http://www.er.doe.gov/bes/user_facilities/dsuf/nanocenters.htm) and the National Institute of Standards and Technology (NIST; http://www.cnst.nist.gov/nanofab/about_nanofab.html) (see Sects. 8.6 and 8.7, respectively). Appendix D has an extensive listing of the user facilities and other various university nanotechnology R&D centers and institutes that also have extensive instrumentation capabilities, most established in the last decade.

## 2.2 *Education Drivers: New Fundamental Knowledge and Nano-Enabled Technology Innovation*

Stimulated by the various nanotechnology programs around the globe [46], progress in nanoscale science and engineering over the past decade has been phenomenal. There were seven professional science/engineering journals with a nanotechnology focus in 2000; there are now over 90. The knowledge base has been growing exponentially, with the annual number of science/engineering professional publications increasing from 600 in 1990, to 13,700 in 2000, and to 68,000 in 2009.[1] The discoveries described in those many publications provide new knowledge that must be incorporated into the educational corpus.

Some examples follow of government and/or private programs created in response to the growing recognition in the past decade that nano-enabled technologies can be key contributors to solving problems of national priority:

- Information technology devices became nanoscale in three dimensions in about 2003 when the 90 nm semiconductor process node was realized; that became 45 nm in 2007, with 22 nm expected by 2012. Early in the 2000s, as the semiconductor industry looked forward, it realized the need for alternatives to complementary metal-oxide-semiconductor (CMOS) electronic devices, which face problems with continuing miniaturization, including quantum complications and heat dissipation. To accelerate progress in finding alternatives, the Semiconductor Research Corporation entered into a partnership with the National Science Foundation to establish a Nanoelectronics Research Initiative (NRI; http://nri.src.org/). SRC created four multidisciplinary NRI centers, with additional industry funding at selected NSF centers. NSF instituted a university program on "Science and Engineering Beyond Moore's Law" in 2009 (SEBML; http://www.eurekalert.org/pub_releases/2010-02/nsf-nsi020110.php) and a joint NSF-NRI solicitation "Nanoelectronics for 2020 and Beyond" in 2010 (NEB, NSF 10–614, with $18 M NSF and $2 M NRI funding) as part of the SEBML.
- There is growing awareness of the nanoscale role in medicine and health [10–12]. The annual investment by NIH in the NNI has grown from $32 million in 2000 to $360 million in 2010. A search on professional literature publications addressing the nanoscale in medicine and biology shows exponential growth beginning in roughly 2000: there were about 1,000 papers in 2000 compared with 11,000 in 2009.[2] A number of multidisciplinary centers for R&D in nanotechnology in medicine have been created, especially by the National Cancer Institute (NCI; http://nano.cancer.gov/; see Appendix D). A number of clinical trials utilizing nano-enabled technologies are in progress (see Sect. 8.10); MagForce Nanotechnologies AG received European regulatory approval for its Nano Cancer therapy in 2010.[3]
- DOE annual investment in the NNI has grown from $58 million in 2000 to $373 million in 2010, a reflection of the growing awareness of the role of nanotechnology in renewable energy and energy conservation (see http://www.nano.gov/html/about/symposia.html and http://www.energy.gov/sciencetech/nanotechnology.htm). Many, if not most, of the awardees of the DOE Energy

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[1] These numbers are based on a simple keyword "nano*" search of the Thompson ISI Web of Science database; while easy to perform, this search generally undercounts the number of pertinent publications.

[2] This count is based on a keyword "nano* AND medic* OR nano* AND bio*" search of the Thompson ISI Web of Science database.

[3] http://www.magforce.de/english/home1.html

Frontier Research Center (EFRC) competition in 2009 had major nanoscale components in their research program (see Appendix D).
- The U.S. EPA has fostered nanoscale approaches to green manufacturing [13, 14]. Nanostructures are being exploited for environmental remediation, with careful attention to environmental, health, and safety issues [15].
- The nanoscale is expected to enable many innovative technologies that will lead to new jobs. Small businesses are a major contributor of new jobs. For several years Federal SBIR/STTR funds have been devoted to the transition of nanoscale research discoveries into innovative technologies, with ~$100 million awarded in 2008 alone [16]. The NIST Technology Insertion Program (TIP) has also funded nanotechnology efforts.

## *2.3 Education: Public/Informal, College/University, Community College, K–12*

Education must evolve quickly to reflect the growing knowledge of the nanoscale and its application to new technologies. A perspective on the present status and challenges in NSE education can be found in several recent major reports and in the workshop report *Partnership for Nanotechnology Education* [7]. Education is a long-term investment; returns take at least one generation to become evident. Ten years ago, the NSF had the foresight to begin funding nanoscale education (formal and informal), together with research on the societal impact of nanotechnology [17]. The NNI agencies as a group have taken a multipronged approach to funding nanoscale education. The significant progress over the past decade in nanoscale science and engineering education can be reviewed in several workshop reports of the National Center for Learning and Teaching in Nanoscale Science and Engineering Education [18–20]. Table 1 lists a number of websites with educational materials addressing the nanoscale; in addition, various nanoscale research center efforts include educational programs.

### 2.3.1 Status of Public/Informal NSE Education

The Nanoscale Informal Science Education Network (NISE Net) was established in 2005 for the purpose of creating a national infrastructure of informal science education institutions, in partnership with nanoscale science research centers. It was aimed at raising public awareness, understanding, and engagement with nanoscale science, engineering, and technology. In scanning the 2005 environment in which the NISE Net set out to achieve those impacts, [47] identified four major challenges:

- The content and pedagogy of nanoscale education was just then emerging.
- The field was just learning how to design informal education resources that will effectively communicate the nanoscale to public audiences in informal science education settings.

**Table 1** Websites with nanoscale science and engineering educational content

| Organization/institution | URL |
|---|---|
| Access nano (Australia) | http://www.accessnano.org/ |
| American Chemical Society | http://community.acs.org/nanotation/ |
| European Nanotechnology Gateway | http://www.nanoforum.org |
| Institute of Nanotechnology | http://www.nano.org.uk/CareersEducation/education.htm |
| Intro to nanotechnology | http://www.nanowerk.com/news/newsid=16048.php |
| McREL classroom resources | http://www.mcrel.org/NanoLeap/ |
| Multimedia educ. & courses in nanotech (largely European) | http://www.nanopolis.net |
| NanoEd resource portal | http://www.nanoed.org |
| NanoHub | http://nanohub.org/ |
| Nanoscale Informal Science Education Network | http://www.nisenet.org |
| NanoSchool box (Germany) | http://www.nanobionet.de/index.php?id=139&L=2 |
| Nanotech KIDS | http://www.nanonet.go.jp/english/kids/ |
| Nanotechnology Applications and Career Knowledge (NACK) Center | http://www.nano4me.org/ |
| Nanotechnology news, people, events | http://www.nano-technology-systems.com/nanotechnologyeducation/ |
| NanoTecNexus | http://www.Nanotecnexus.org |
| NanoYou (European Union) | http://nanoyou.eu/ |
| Nanozone | http://nanozone.org/ |
| NASA Quest | http://quest.nasa.gov/projects/nanotechnology/resources.html |
| National S&T Education Partnership | http://nationalstep.org/default.asp |
| NNI Education Center | http://www.nano.gov/html/edu/home_edu.html |
| NNIN Education Portal | http://www.nnin.org/nnin_edu.html |
| NSF Nanoscience Classroom Resources | http://www.nsf.gov/news/classroom/nano.jsp |
| PBS – DragonflyTV | http://pbskids.org/dragonflytv/nano/ |
| Taiwan NanoEducation | http://www.nano.edu.tw/en_US/ |
|  | http://www.iat.ac.ae/downloads/NTech/UAE_Workshop_Pamphlet2.pdf |
| The Nanotechnology Group, Inc. | http://www.tntg.org |
| Wikipedia | http://en.wikipedia.org/wiki/Nanotechnology_education |

- At the informal science education (ISE) institutional level, there was little expertise, experience and incentive to do nanoscale education for the public.
- At the field level, there was limited experience in developing and working within a national supportive network.
- Between 2005 and 2009, the NISE Net made significant progress in addressing all four of these challenges, with the result that by 2009, it could be said that: "Overall, NISE Net has created a large-scale functioning network that is capable of promoting nanoscience education for the public across the nation. In the past 4 years NISE Net has developed strong and distributed leadership, built relationships

with hundreds of individuals and institutions, created functional organizational and communication structures, and developed an initial collection of programs and resources that are flexible and valued by the field. In these ways NISE Net has established itself as a knowledgeable and valuable resource for both informal science educators and nanoscience researchers. (Inverness Research Associates 2009)"

- While the concepts of nanotechnology were virtually unknown to the public 10 years ago, in a 2009 national survey of adults, 62% said they had heard at least a little about nanotechnology [21]. While this increase cannot be attributed specifically to informal science education, the capacity to engage the public in a wide range of topics related to nanoscale science and technology has grown significantly in the last decade. Nanoscale science research centers, often in partnership with science museums, have engaged in a wide range of educational outreach activities, some focused on reaching public audiences and some on reaching K–12 school audiences. These collaborations have produced hands-on activities for classrooms and science museums; exhibits for science museums and even the EPCOT Center at Disneyworld; activities for the museum floor and for out-of-school programs; and various kinds of media content for magazines, websites, and even large-screen theaters.

Data suggests that the public in the United States is generally supportive of research and development in the area of nanotechnology, even in the absence of detailed knowledge about it.[4] Those with knowledge and awareness generally seem to support it more than those who do not. Gaining knowledge about nanotechnology R&D, however, does not necessarily translate to increased support; it may translate to increased awareness of potential risks, which may increase uncertainty about whether benefits will exceed risks. On the other hand, awareness of risks need not translate into decreased support [22]. Public views on risks versus benefits of nanotechnology show a significant neutral response: about one half of respondents either gave a neutral response (benefits equal risks) or they said they did not know [48], which suggests that these opinions are open to change as Americans become more familiar with nanotechnology. A more recent study showed nanotechnology ranked 19th out of 24 in terms of overall risk when compared with other selected hazards [23].

Education efforts are likely to help Americans become familiar with nanotechnology slowly over time, but a significant newsworthy event is likely to have a larger and more immediate impact. Will the future events be a great breakthrough in something the public cares about dearly, or will it be some kind of accident or disaster? Either of these scenarios would wake public attention to nanotechnology and provoke a dramatic change in awareness. Which will come first? How do we prepare to handle public information, questions, and concerns if the future event is an accident of some kind?

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[4] Flagg, B. Nanotechnology and the Public, Part 1 of Front-End Analysis in Support of Nanoscale Informal Science Education Network, 2005, http://informalscience.org/evaluations/report_149.pdf.

### 2.3.2 Status of College/University NSE Education

Most research-intensive universities now have nanotechnology-related science and engineering courses, many have centers or institutes focused on the nanoscale, and several have nanotechnology-oriented departments and colleges. As an example of the latter, the new campus of the College of Nanoscience and Engineering at the State University of New York University at Albany (http://cnse.albany.edu/about_cnse.html; see also Sect. 8.5) is seamlessly integrated with collaborating micro- and nanoelectronics companies.

There has been significant progress in the incorporation of NSE concepts into curricula and textbooks at the college- and graduate-school levels [7]. Nanoscience-based courses are being rapidly introduced at 2-year colleges, 4-year colleges, and universities (see listings at NanoEd Resource, http://www.nanoed.org/ and [7]). A number of 4-year-degree-granting institutions in the United States have created minors or concentrations in nanotechnology. These are generally comprised of 18 credits of nanotechnology courses combined with courses fundamental to nanotechnology such as quantum physics and physical chemistry. These minors allow students to graduate from engineering (e.g., electrical engineering, chemical engineering) and science programs (e.g., physics, chemistry, biology) with a minor (or concentration) in nanotechnology. An example of this approach is the nanotechnology minor at The Pennsylvania State University (see Sect. 8.3 and Appendix D in Murday [7]). The NSF Research Experience for Undergraduates (REU) program is an effective vehicle for introducing undergraduates to nanoscale research projects. The NUNN/NNIN REU program alone has given over 600 undergraduate students the opportunity to conduct nanotechnology research.

Several approaches to introducing NSE concepts into undergraduate education have been utilized in the past decade:

- *Supplemental approach*: The practice of inserting fundamental NSE concepts into existing courses has been successful around the country.
- *Inquiry and design principles approach*: Concept modules using the principles of inquiry and design were pioneered by the NSF-funded Northwestern University program, “Materials World Modules” (MWM; http://www.materialsworldmodules.org/). Discovery comes with asking the “right” question. Effective design requires a sound knowledge of the nanoscale concept to be applied. Each module includes a series of inquiry-based activities that culminate in a team-based design project. These principles have been successful in engaging students at the undergraduate level.
- *Cascade approach*: This method allows older students to learn and reinforce concepts in the process of teaching them to younger students, resulting in a “cascade” of learning from one student group to another. Older students gain a deeper understanding of the concepts studied, experience in creative thinking and design, and improved inquiry and communication skills. Younger students gain more exciting, age-appropriate instructional materials and are inspired by their slightly older peers’ interest in science and engineering. In both cases, participating students

have designed some amazingly innovative activities, which include card games, web-based games, and simulations of nanoscale phenomena. The “Teach for America” program for students to take time off to teach demonstrates as that peers of comparable age (in this case, undergraduate college students) can communicate very effectively with younger (middle school) students [24].

An exciting trend is that more and more young professors are interested in science education, including nanoscale education, and are beginning to work with precollege teachers and their students. Graduate programs such as those offered by NSF science center programs, Graduate STEM Fellows in K–12 Education [25], Integrative Graduate Education and Research Traineeship [26], and others, provide opportunities for graduate students to become involved in teaching their junior peers.

### 2.3.3 Status of Community College NSE Education

Forty percent of U.S. college and university students overall begin their education in community colleges [27]; the statistics are higher for minority populations. Since it is estimated that present minority populations will be in the majority of schoolchildren by 2023 [28], the role of community colleges in teaching nanoscale science and technology to American students and workers may become even more significant than it is today.

Economic pressures can arise when community and technical colleges feel that they must create four semesters of new courses for 2-year degree programs in nanotechnology. The high costs can contribute to the reluctance of administrators to involve their institutions in nanotechnology education. Four-semester nanotechnology programs also create student enrollment pressures: there must be a “critical-mass” of student enrollment generated each semester to justify running such programs. Faculty, staff, and facilities resource issues arise with the realization that a meaningful nanotechnology education must expose students to state-of-the-art tools of nanotechnology fabrication and, most importantly, characterization. Often, 2-year institutions do not have the resources required to provide this exposure. Further, in areas of the United States, 2-year institutions find themselves relatively geographically isolated, precluding interactions with industry or research universities with nanotechnology facilities resources.

Several NSF-supported nanoscience-oriented Advanced Technological Education (ATE) programs (see National Science Foundation (NSF) [4], Appendix D, and Sect. 8.3) focus on training future nanoscale technicians. Students participating in these programs acquire classroom knowledge and high-tech industrial laboratory experiences. The National ATE Center for Nanotechnology Applications and Career Knowledge (NACK), created in 2008 by NSF, is charged with augmenting and further developing nanotechnology education at 2-year degree institutions across the United States. NACK offers nanotechnology courses that may be attended or viewed on the web, course units on the web, state-of-the art equipment

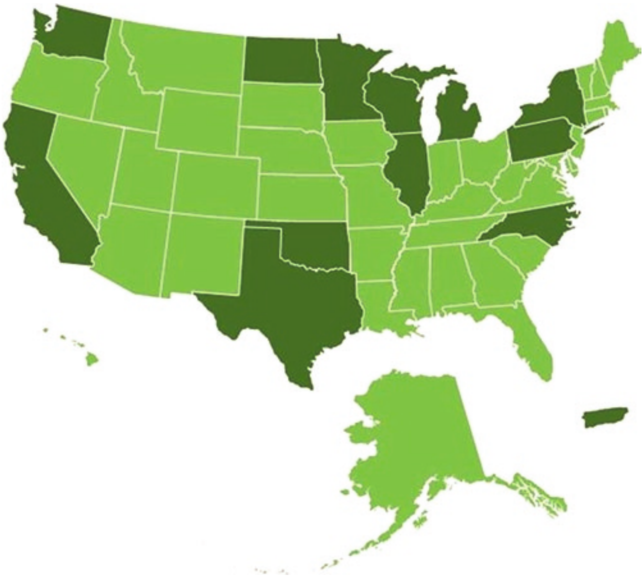


**Fig. 2** *Darker shading* indicates states that have 2-year degree institution nanotechnology programs associated with NACK (from http://www.nano4me.org)

utilization experiences that may be attended or utilized on the web, web access to characterization equipment, and workshops on teaching nanotechnology. All information and web access is through the NACK website http://www.nano4me.org. Figure 2 is a map of regions that have nanotechnology programs at 2-year degree institutions.

### 2.3.4 Status of K–12 NSE Education

The pre-college level is where educational systems begin preparing nano-literate citizens, training future nano-technicians and engineers, and using nanoscale concepts to pique student interest in STEM. The lack of student interest in science/engineering is endemic in economically advanced countries [29] and constitutes a severe mid- to long-term threat for future economic and quality-of-life growth if academia and industry should fail to find the needed science/engineering workforce.

In the United States, impediments to achieving these education needs include the fact that each state has its own set of standards and learning goals, and there are significant disparities in standards between states and between individual school districts. Educational standards are of urgent importance to teachers who must prepare their students to perform well on standardized tests. The Council of Chief State School Officers (CCSSO) and the National Governors Association (NGA) are leading a common core learning standards effort (http://www.corestandards.org/) based on international benchmarking. The Mathematics and the English Language

Arts standards were released (June 2010) and have been adopted by 35 States by October 2010. The sciences will be the next topic to be addressed. The National Research Council (NRC) Board on Science Education (BOSE; http://www7.nationalacademies.org/bose/BOSE_Projects.html) has been working on a conceptual framework for new science education standards. A draft incorporating core disciplines of life sciences, earth and space sciences, physical sciences, and engineering and technology was released for public comment in August 2010; the revised version is due for release early in 2011.

NSE educational concepts are being linked to existing STEM standards and learning goals at the state and national levels. A series of fundamental NSE concepts (e.g., surface-area-to-volume ratio, size and scale, size-dependent properties, dominant forces, quantum phenomena, self-assembly, tools for nanoscale characterization, and others), have been mapped to STEM concepts that already are being taught in U.S. classrooms. These concepts are also being aligned with the national science standards developed by American Association for the Advancement of Science (AAAS), the National Science Education Standards [30], the national math standards developed by the National Council of Teachers of Mathematics (NCTM), and various state standards. This work is paving the way for nanoscale content to be inserted into a broad range of STEM courses, including Biology, Chemistry, Mathematics, Physics, Technology, Engineering, and General Science.

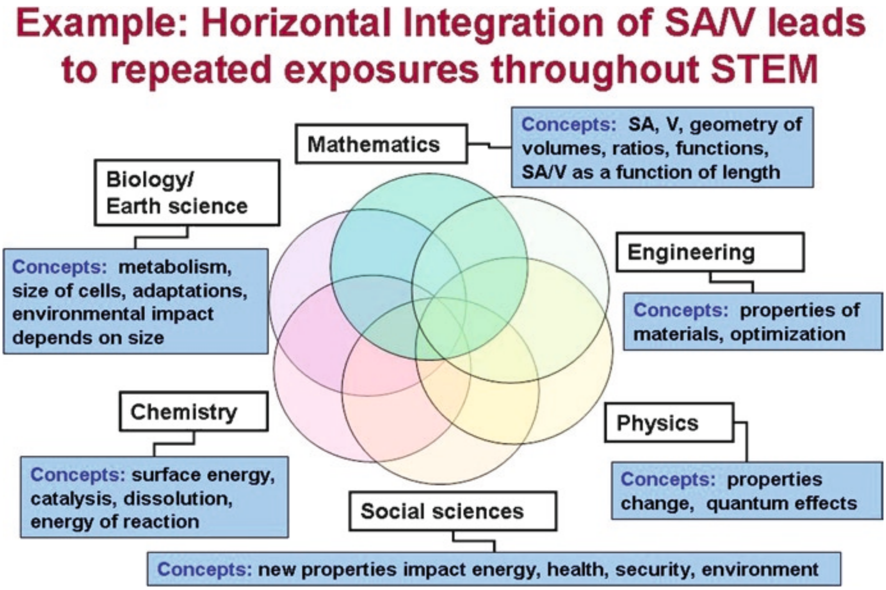
NSE does have a "wow" factor that gets students excited about STEM and motivates them to learn. Experience in U.S. classrooms demonstrates that students find the nanoscale both exciting and intriguing, especially when they are applied to new technologies and real-world challenges. Given that lack of student interest is a critical challenge facing STEM education nationally, and in many developed countries, this effect must not be undervalued. Nanoscale science concepts and their applications help students connect STEM to their everyday lives, and this motivates them to learn. In the words of one Nashville teacher, "We all want to be wowed, amazed, and captivated. If education can do this and teach important concepts, students will beat the doors of the school down demanding more. Nanotechnology fills the bill."

Many programs already have a strong nanotechnology education and outreach component:

- A number of NSE education research centers with funding from NSF, DOE, and other agencies are charged with transferring these concepts into U.S. classrooms. Examples are the NSF Nanoscale Science and Engineering Centers (NSEC) and the DOE Nanoscale Science Research Centers (NSRC).
- Other programs such as the NSF Materials Research Science and Engineering Centers (MRSEC), Engineering Research Centers (ERC), and Science and Technology Centers (STC) have also developed NSE education components. Activities vary among centers but may include classroom outreach, content development, and teacher professional development, often with funding from the NSF Research Experiences for Teachers (RET) program.
- Other new nano-specific education projects have been funded under existing programs. For example, the NSF has funded nano-specific learning research by BSCS, Nanoteach, and McREL (see Table 1).

Challenges abound to engaging students in nanoscale science and technology. A large percentage of teachers are not prepared to teach mathematics and science. Further, their curricula are already so crowded that it is difficult to see where new topics can be added. And once these challenges have been considered, how can we teach students about what they cannot directly see or feel? How can we give them a real "nano" experience without bringing expensive, high-tech equipment into their classrooms? How can we make clear connections to real-world applications and future careers? Horizontal and vertical integration of NSE education programs is viewed as necessary to achieve the goals of educating the workforce, changing formal and informal education, and having an informed public.

*Horizontal integration*: In most schools, STEM is taught from distinct (traditional) disciplinary perspectives. While these perspectives can be useful, they can also result in student understanding that is disjointed and isolated from real-world systems and applications. Because NSE education concepts describe phenomena that occur across all STEM disciplines (e.g., see Fig. 3), these concepts transcend traditional disciplinary boundaries. In particular, Chemistry, Physics, and Biology merge at the nanoscale, addressing similar problems using similar techniques. In addition, at the nanoscale, unique materials properties and complex fabrication techniques require a merging of science and engineering. It is therefore quite natural to take an integrated "systems" approach to learning and teaching nanotechnology. Moreover, compelling connections can be made to social studies, physical education,


Example: Horizontal Integration of SA/V leads to repeated exposures throughout STEM

Mathematics

Concepts: SA, V, geometry of volumes, ratios, functions, SA/V as a function of length

Biology/ Earth science

Concepts: metabolism, size of cells, adaptations, environmental impact depends on size

Engineering

Concepts: properties of materials, optimization

Chemistry

Concepts: surface energy, catalysis, dissolution, energy of reaction

Physics

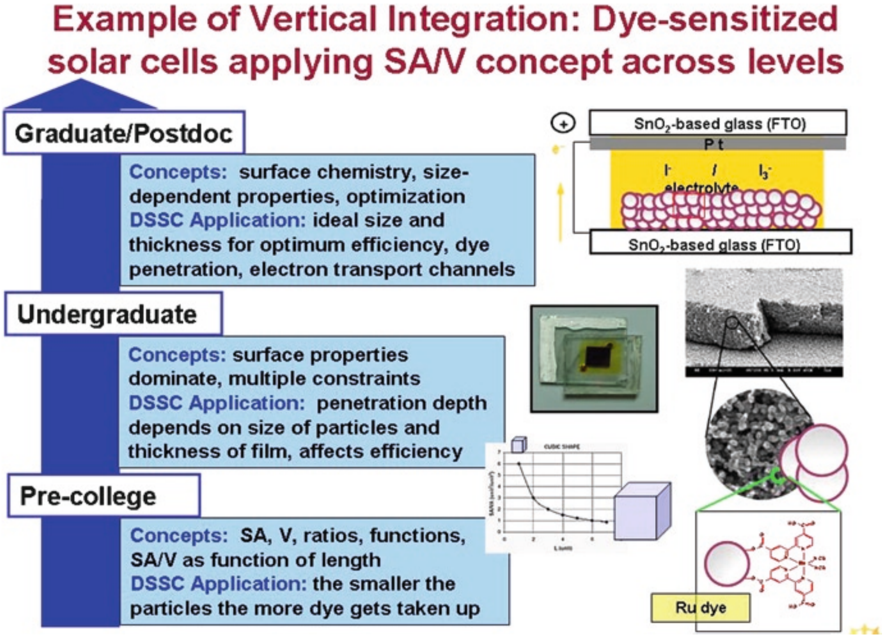
Concepts: properties change, quantum effects

Social sciences

Concepts: new properties impact energy, health, security, environment

**Fig. 3** Example of the horizontal integration of nanotechnology knowledge of surface-area-to-volume (SA/V) ratio, leading to repeated exposures of this concept to students in STEM and other subjects (Courtesy of Nanotechnology Center for Learning and Teaching) and the arts that increase the relevance of nanoscale science and technology to society and the economy. Taking a horizontal, transdisciplinary approach provides the opportunity to teach STEM in an integrated way and enables students to appreciate the natural overlap of these disciplines. Moreover, it serves to unify STEM curricula by allowing students to experience a nanoscience concept repeatedly from different angles and in different contexts. Public school districts in Los Angeles and Nashville are piloting integrated science curricula that use nanoscale science as a core (or unifying) discipline and link NSE concepts to both STEM and non-STEM courses.

*Vertical integration*: Our current educational structure is often characterized by large achievement and learning gaps between levels. Incorporating nanoscale education into grades 7–16 affords an opportunity to study how students learn fundamental nanoscience concepts at each level, to monitor student longitudinal progressions, and to develop learning trajectories to guide effective teaching across levels. The learning research suggests that teaching the same fundamental NSE concept (such as size and scale or SA/V ratio; see Fig. 4) at multiple grade levels can result in deeper understanding of STEM concepts and in more efficient transitions from one grade level to another. This vertical integration is both time-saving and effective.



Example of Vertical Integration: Dye-sensitized solar cells applying SA/V concept across levels

**Graduate/Postdoc**

Concepts: surface chemistry, size-dependent properties, optimization
DSSC Application: ideal size and thickness for optimum efficiency, dye penetration, electron transport channels

**Undergraduate**

Concepts: surface properties dominate, multiple constraints
DSSC Application: penetration depth depends on size of particles and thickness of film, affects efficiency

**Pre-college**

Concepts: SA, V, ratios, functions, SA/V as function of length
DSSC Application: the smaller the particles the more dye gets taken up

Fig. 4 Example of vertical integration of nanotechnology knowledge for dye-sensitized solar cells, applying the concept of SA/V ratios at higher conceptual levels over time (Courtesy of Nanotechnology Center for Learning and Teaching)

### 2.3.5 International Integration

The U.S. K–12 STEM education does not compare well with that of many countries around the world, especially those with whom U.S. businesses must compete for new markets. A recent report by the National Governors Association and Council of Chief State School Officers emphasizes the need for international benchmarking as a means toward improvement of educational standards [28]. Since nanotechnology research, development, and deployment are growing globally, all countries (but especially the United States) can benefit from learning what works best in the incorporation of the nanoscale into STEM curricula in other countries of the world.

# 3 Goals, Barriers, and Solutions for the Next 5–10 Years

The remarkable progress in nanoscale research discovery, coupled with the growing opportunities in innovative nano-enabled technology, presents new infrastructure challenges. In the next 10 years, while sustaining the discovery progress, how might the transition from discovery into technology be accelerated? Further, by virtue of its inherent transdisciplinarity, its fascinating real-world applications, and its immediate relevance to future career opportunities, nanoscale science education is an ideal means of increasing student interest and achievement in STEM disciplines. A national strategy should be developed to expand the current efforts in STEM/NSE education, to help ensure that citizens around the world can reap the economic, social, and educational benefits of nanotechnology.

## *3.1 Physical Infrastructure*

There has been truly impressive growth in nanoscience/engineering facilities over the past decade. A prime goal is to fully exploit those facilities for science and engineering, while continually adding new capabilities as they are developed. It is vital to critically assess their utilization and effectiveness, followed by corrective actions, if needed to gain higher efficacy.

While new analytical and fabrication tool development over the past 20 years have provided many impressive new capabilities (see in chapter "Investigative Tools: Theory, Modeling, and Simulation and Sect. 8.13 for examples), a number of NNI workshops have pointed toward the importance of persisting in advanced tools development.[5] When these tools are either expensive and/or difficult to operate,

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[5] Nanomaterials and Human Health & Instrumentation, Metrology, and Analytical Methods (November 17–18, 2009); Nanomaterials and the Environment & Instrumentation, Metrology, and Analytical Methods (October 6–7, 2009); Nanotechnology-Enabled Sensing (May 5–7, 2009); X-Rays and Neutrons: Essential Tools for Nanoscience Research (June 16–18, 2005); Nanotechnology Instrumentation and Metrology (January 27–29, 2004). See http://www.nano.gov/html/res/pubs.html for associated publications.

they must be added into the national user facilities to make them accessible to a wide variety of users, including teachers and students.

The international workshops all pointed to a new R&D facility need. The success of centers addressing fabrication and characterization for discovery needs to be emulated in a new suite of centers whose focus will be on the transition (or translation) of discovery into innovative technology.

## *3.2 Informal/Public Outreach in NSE*

Having successfully built a network focused on, and capable of, providing nanoscale informal educational experiences to the public, the goal of NISE Net for the next 5 years should be to use that network to expand the number of people it reaches to the millions. To accomplish this goal, objectives include the following:

- Perform a SWOT analysis of the public outreach to determine the value to current activities, and use this benchmark data to design efficient and effective public education models
- Deepen the involvement in nanoscale ISE of over 100 institutions (universities, museums, public radio, etc.) and expand their nanoscience and technology offerings by infusing "nano" content throughout their educational programming
- Leverage resources through connections with other networks of informal educators and researchers to further spread the reach of NSE education for audiences in both informal and formal educational settings
- Develop sustainable partnerships between informal educational institutions and research institutions that can provide ongoing benefits to both when NISE Net funding expires
- Explore electronic media for innovative approaches to reaching youth who are adopting these new communications mechanisms

More broadly, two interrelated strands of educational activities should continue: preparation of the future workforce and preparation of consumers and citizens.

### 3.2.1 Preparation of the Future Workforce

Preparation of the future workforce is strongly associated with formal education but is supported by informal science education as well. From an informal education perspective, aspects of future workforce preparation should take place in four stages.

- *Stage 1 – Primary (grades K–5)*: The goal for ISE education for young children is to grow their interest in science, technology, engineering, mathematics – and society in general (STEMS subjects). This can include fostering a fascination with unusual properties of materials, size-dependent phenomena, and other topics related to the nanoscale, but it is not yet important that students recognize nanotechnology as a separate research field. Development of materials and educators' professional qualifications within informal science education should help support the work of this stage to build general interest in STEMS and to add nanoscale-related phenomena to existing science-based activities.

- *Stage 2 – Secondary (grades 6–12)*: The goal for ISE for middle school and high school youth is to build their underlying knowledge, awareness, and skills in STEMS while maintaining and growing their interest. Informal education should also help inform parents about areas of STEMS that their children might find of interest as potential careers. Highlighting applications and societal implications can also be a motivating factor.
- *Stage 3 – College*: The goal for ISE for undergraduate and graduate students is to give them the opportunity to contribute to public and K–12 educational activities by presenting their research and talking with the public about it. Developing this ability among future scientists is key to the education of consumers and citizens and can help students think about the big issues in their research and their careers.
- *Stage 4 – Workplace*: The goal for ISE in the workplace is to increase the number of scientists, engineers, and technicians who can work in nanotechnology by retraining; for their education as consumer and citizens; and can contribute their knowledge in various informal educational environments to public and K–12 educational activities.

### 3.2.2 Preparation of Consumers and Citizens

In the absence of either a noteworthy breakthrough or a severe accident involving nanotechnology, widespread public education activities can and should build public awareness of nano-enabled technologies. An emphasis on the nanoscale as an essential pathway to resolving societal problems, such as renewable energy, health/medicine, and environment, might frame the nanoscale in terms more conducive to public interest. The public presently does not believe nanoparticles are particularly risky per se (Berube et al. submitted). In the absence of an immediate reason for the public to care personally about nanotechnology, this is likely to be incremental and slow and needs to be sustained to have long-term impact. This requires continually paying attention to increasing public awareness and knowledge at a measured pace while building the capacity of informal educators and other science communicators to inform the public as future events raise the level of public awareness and interest. It is also necessary to develop the capacity for the public to assess the benefits and risks of nanotechnology and to gain a genuine capacity to influence policy. As Lee and Scheufele [31] have noted:

> Public outreach is not a matter of promoting pro-science views among the general public or simply improving literacy. Public outreach involves effective communication with all stakeholders (scientists, citizens, policy makers, etc.) Currently, public debate about issues such as stem cell research is dominated by ardent interest groups and partisan players. Scientific views are not heard.

For the public, key factors in dealing with uncertain risk are trust and control. Data shows that the public wants both information and government regulation. The public feels that university scientists are a trustworthy source of information about nanotechnology. The public also has a high level of trust in science museums. The government and news media are least trusted "to tell the truth about the risks and benefits of nanotechnology". According to research conducted in connection with the Center for Nanotechnology in Society, "university researchers and scientists working for nano businesses are among the most trusted sources for information about nanotechnology" (Scheufele 2007). Unpublished results from the same study, however, show that government and news media are least trusted to tell the truth about the risks and benefits of nanotechnology.

All of this suggests a strategy for public education and engagement that overlaps with governance – that is, creating a science/technology governance structure that better involves the public. There is a need to build two-way communication between scientists and public and to include assessment of risks and benefits in the dialogue. Far exceeding the number of informal science educators, the scientists, engineers, and technical staff in the United States can be a valuable resource in talking with the public, but they need to be given the tools to do so effectively. Mechanisms need to be created to effectively engage the public in long-term thinking about societal implications, risks, and benefits, and about issues regarding government controls, regulation, and priorities in nanotechnology research and development.

In order to achieve this proactive kind of governance and public engagement model, collaborations should be fostered among science research institutions, social science institutions, and informal science education institutions, with a specific focus on developing:

- Easy-to-communicate notions about the future promise of research and ways to equip informal educators and scientists to communicate with the public about these ideas
- Broad knowledge about societal implications of future technologies, ways to equip informal educators and scientists to consider such issues in connection with their work, and ways to communicate with the public about them
- Mechanisms for public participation in technology assessment that fosters dialogue between scientific and public participants, leading to informed public involvement in policymaking

## *3.3 College/University NSE Education*

Nanoscale science and engineering discoveries will continue to develop at a rapid pace; innovative, nano-enabled technologies already are penetrating the marketplace. The implications for undergraduate and graduate education are likely to be profound, but hard to anticipate. There needs to be continuing dialog and ongoing experimentation on curricula and degree requirements, working with industry to assure relevance to the workforce. Since the research into NSE is truly international in scope, an important goal is to provide experience in international venues as part of the degree process. A year "abroad" has long been valued as part of a liberal arts education; some variant on this idea should also be considered for nanoscale science/engineering education. Post-doctorate work abroad should be encouraged for scientists, but so should opportunities for other students, so as to serve not only those science students looking toward university research careers but also those students looking towards careers in business and industry.

Although no mandated teaching and learning standards exist at the college level (beyond professional accreditation), strong disciplinary boundaries are reinforced both by the accreditation process and by competition of departments for funding and resources. These disciplinary boundaries are often more rigid than those at the pre-college level. Priorities for improving NSE education at the college level include developing innovative nanoscale courses and degree programs, fostering cross-disciplinarity, and supporting NSE education community-building through faculty workshops, content development workshops, online content sharing, and networking events. Global partnering to share content and best practices will be essential in the new "flat world."

The weakest NSE elements in university education involve nanoscience education for students who are not majoring in science or engineering. Incorporating science-related societal issues as a meaningful component of liberal arts courses, and other creative interfaces for students in science and education, would offer opportunities to increase science/technology literacy and advocacy.

### *3.4 Community College NSE Education*

While U.S. research universities are acknowledged as world leaders in science and engineering, competition is growing globally – especially at the nanoscale. To meet national needs for researchers in the near future, it will become more important to nurture U.S.-born students' interest in STEM. Because 40% of college students get their start in community colleges, the Opportunity Equation report [27] recommends closer interaction between community colleges and the universities. NSF, the Department of Education (DoEd), and other agencies with relevant missions must have a goal to foster nanoscale curricula development and evaluation that is appropriate for community colleges and to ensure meaningful collaborations between community colleges and the national nanocenters and networks. Nanotechnology should be included in DoEd's Department of College and Career Transitions program.

### *3.5 K–12 NSE Education*

A primary goal in education is the insertion of NSE into national and state K–12 standards of learning. Incorporation of NSE into K–12 curricula and textbooks has lagged the rapid development of new scientific knowledge about the nanoscale.

If this is to be rectified, it will be essential to introduce nanoscale science/engineering into the various state learning standards that effectively determine what is taught in primary and secondary school classrooms. Otherwise curriculum changes at the K–12 levels of education will be minimal, and increasing nanoscience literacy toward a productive workforce will not be maximized [7]. A key objective is to identify the fundamental nanoscale concepts and to map them onto existing state and national STEM learning standards such as the American Association for the Advancement of Sciences Benchmarks for Science Literacy (http://www.project2061.org/publications/bsl/default.htm), the National Science Education Standards [30], and the National Council of Teachers of Mathematics Standards and Focal Points (http://www.nctm.org/standards/default.aspx?id=58). Nanoscience educators should also work with these organizations to integrate specific nanoscience concepts into the standards and cooperate with organizations now working to nationalize learning standards. Increasing the connections between NSE/STEM and non-STEM disciplines such as social sciences, business sciences, language arts, sports, and fine arts also will help students understand the relevance of NSE and STEM to their everyday lives and to solving global challenges in energy, environment, health, communications, and others.

In the U.S. the National Governors Association has approached Achieve, Inc., with the task of preparing internationally benchmarked, common core learning standards in the sciences that might be adapted by each state for its own academic content standards. The National Science and Technology Council's National Science, Engineering and Technology Subcommittee (NSET), which coordinates NNI endeavors, has initiated contact with the National Governors Association, the Council of Chief State School Officers, and Achieve, Inc., to support their efforts to appropriately introduce the nanoscale into common core educational standards for developmental progression in the sciences (life, physical, earth/space) and engineering/technology. Assistance should be provided to those efforts. Because each state will determine its own process, participants in the many Federal centers for nanotechnology R&D should begin working with their own state departments of education toward forward-looking revision of their science learning standards.

### 3.5.1 K–12 Curricula

Standards provide the target; curricula provide the means. To regain prominence in science, technology, and engineering, the United States must stop having a haphazard approach to curriculum development. Funding is needed to allow for the design, development, testing, and implementation of coherent NSE curriculum models that will allow 7- to 16-year-old students to develop an integrated understanding of core science ideas that underpin nanoscale science and engineering. Such curricula should focus on helping students develop progressively deeper understanding of the core ideas.

### 3.5.2 K–12 Teaching Aids

The sciences (biology, chemistry, earth/space, and physics) and engineering require hands-on experiences as part of the learning process. While inclusion of laboratory work at local schools is a necessity, some laboratory learning may be beyond the capability and/or budget of local schools and personnel. The NNIN, NSEC, and DOE nanocenters, and the NIST Center for Nanoscale Science and Technology should have a goal to work with the National Science Teachers Association and the DoEd toward the preparation of on-site and/or remote access to high-end laboratory facilities that can contribute to the K–12 NSE education process.

### 3.5.3 Teacher Education and Training (Professional Development)

There will be growing inclusion of nanoscale science, engineering, and technology into standards of learning. There are also growing learning resources that address nanoscale science, engineering, and technology. Teachers will need to be trained to use these resources, and there must be a goal to provide that training. The nation's nanocenters can be a vital resource to provide materials, training, and information. They should be encouraged to be more proactive toward K–12 teacher training.

Person-to-person contact remains the most effective mode of teaching and learning. The various university-based nanocenters should mobilize their undergraduate and graduate students to engage in K–12 education at the nanoscale. Federal funding agencies must provide an adequate budget allowance for this work. In tenure and promotion decisions, universities must recognize the efforts of their faculty to supervise activities of their students who are engaged in teaching nanoscience concepts to younger students.

## *3.6 Across NSE Educational Levels: Global Partnerships and Cyberlearning*

### 3.6.1 Global Partnerships

The challenges in NSE education are global in character. Cooperation with global partners was an explicit topic at the Global Workshop on Nanoscale Science and Engineering Education in November 2008 National Center for Learning and Teaching in Nanoscale Science and Engineering Education (NCLT) [20]. The primary finding at this workshop was that there is a need for an expansive NSE education community, both in real space and in virtual space, to support the development and exchange of resources and build excitement around nanoscale science and engineering education. The NSF Office of International Science and Engineering can potentially play a significant role in helping make this possible.

### 3.6.2 Cyberinfrastructure/Education Through Social Media

Nano-enabled technologies can improve standards of living across the world. With the decline in the last few years in the number of science journalists, there is an opportunity for the NNI agencies, university and industrial programs, and other stakeholder groups to develop a continuing stream of information that can keep the public informed about benefits and risks emanating from nanotechnology-based research and commercialization. The rapid growth in information technologies is creating new interaction paradigms that should be exploited (e.g., Wikipedia, FaceBook, Second Life, YouTube, and Kindle) to reach young and IT-literate learners who use those new media tools [32, 49, 50]. Cyber-education should be included in the suite of learning paradigms to engage students. NSF, with its interest in cyberlearning, should take the initiative, but the DoEd must also be engaged to ensure a continuing effort.

There are a number of websites (such as those listed in Table 1) with materials that address curricula supplements, teaching aids, and science fair projects. The NACK website (http://www.nano4me.org/) is focused on supporting nanotechnology education at 2-year degree granting institutions. In addition, NSF's university-based Nanoscale Science and Engineering Centers (NSECs) have been very productive in terms of developing innovative approaches to NSE education. However, web-based NSE educational materials are widely dispersed, are of non-uniform format, and have varying degrees of refinement. The DoEd, working closely with the National Science Teachers Association (NSTA) and cyber-oriented curriculum developers (such as those listed in Murday [7], Table 6), should create a central website to disseminate the information. The NSTA should serve as the evaluator for quality control to ensure NSE-focused educational website materials are of high quality, are in a format readily utilized by K–12 teachers, are carefully indexed to the various state learning standards, and can be readily accessed from the NSTA website. Additional well-designed, highly interactive, media-rich, online learning tools should continue to be developed.

NanoHUB, the National Center for Learning and Teaching (NCLT), NNIN, NACK, and other cyberinfrastructure resources focused on nanotechnology – all highly beneficial – need to be better publicized regarding accessibility, targeted user levels, customizability (in terms of both targeted audiences and user interface), interoperability with other systems, and service and training offerings. Consideration should be given to the research and development of an overall mechanism for efficient search, access, and use of cyberinfrastructure resources focused on nanoscale science and technology with potential relevance to education at all levels. Such a mechanism would likely entail creating an inventoried, analyzed, tagged registry. Also worth considering are mechanisms to enable greater interoperability with emerging cyber-nanotechnology resources such as remote access to and control of state-of-the-art nanotechnology characterization equipment; properties databases; applications of NSE; environmental, health, and safety implications; and general educational paradigms such as virtual and immersive environments, simulations, and games. Such integration and knowledge sharing offer great promise to accelerate users' discovery of and learning about nanoscale science and technology.

Wikipedia is becoming the de facto encyclopedia of the twenty-first Century. The Wikipedia entries on nanotechnology should be routinely updated and expanded. This task might best be accomplished by mobilizing the impressive variety of talent and expertise at the various nanocenters. K–12 science teachers should be involved to ensure the information is structured in ways that can be readily absorbed by students at various grade levels.

# 4 Scientific and Technological Infrastructure Needs

## *4.1 Facility Infrastructure*

User facilities' budgets must be adequate to provide operating funds and local experts who can assist the novice users in effective use of the state-of-art equipment. There would be value for vetted intellectual property (IP) model agreements that might be used as a trusted basis for companies seeking access to the facilities.

While new analytical and fabrication tool development over the past 20 years has provided many impressive new capabilities (see Sect. 8.13 for recent examples), a number of workshops[6] have pointed out the importance of continuing to do cutting-edge R&D. When these tools are either expensive and/or difficult to operate, they must be added into the user facilities.

As nano-enabled technologies become ever more sophisticated, the equipment needed to make/measure/manipulate will also grow in complexity and cost. International and industrial partnerships need to be fostered as a means of sharing the cost of these new capabilities.

The international workshops all pointed to a new R&D facility need. The success of centers addressing fabrication and characterization for discovery needs to be emulated in a new suite of centers whose focus will be on the transition (or translation) of discovery into innovative technology. This will require user facilities with capability in manufacturing and prototyping. Since there will be a wide diversity in manufacturing/prototyping requirements, a suite of user facilities will be necessary, each addressing a different suite of technologies and processes.

## *4.2 Workforce Development (Industry) NSE Education*

Preparation for employment is an important aspect of the educational process. In our rapidly evolving world, the needs of industry are fluid, due to changing technologies and growing global competition. Nanoscale science will be instrumental

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[6] NIST Workshop on Instrumentation, Metrology, and Standards for Nanomanufacturing (Oct. 17–19, 2006); NNI Workshop on Instrumentation and Metrology for Nanotechnology (Jan. 27–29, 2004); NNI Workshop, Research Directions II (Sept. 8–10, 2004); Chemical Industry R&D Roadmap for Nanomaterials by Design (30 Sept.–2 Oct. 2002).

in technological change. Many countries have followed the lead of the United States and established a nanotechnology initiative [33]. Those initiatives tend to be more focused on targeted technology development than is the United States; consequently, there will likely be strong global competition for people trained in nanoscience and technology at various levels. The Department of Labor needs to work with industry groups and with professional science and engineering societies to develop accurate assessments of domestic nanotechnology-based workforce needs, including the effects of growing education and job opportunities in other countries. These needs must be factored into the educational system.

## *4.3 Informal/Public NSE Education*

A key infrastructure need is educators who are interested in, familiar with, knowledgeable about, and comfortable with teaching nanoscale science, engineering, and technology. This is true in both formal and informal education, but the focus here is informal. This includes educators in science museums, children's museums, university outreach programs, after-school and out-of-school programs, libraries, educational television, radio, and the Internet.

A second infrastructure need is an easily accessible collection of educational materials and activities that can engage the public of various ages with a wide range of nanoscale science, engineering, and technology topics, applications, and societal implications – and that are well suited to the wide range of informal learning environments in which people learn outside of school. In addition to the NiseNET online resources (http://www.nisenet.org/), a superb example can be found at the Munich Deutsches Museum (http://www.deutsches-museum.de/ausstellungen/neue-technologien/), which has a highly interactive exhibit featuring nano- and biotechnologies.

Especially given the decline in the number of science journalists, there is a need and opportunity for the NNI member agencies and the National Nanotechnology Coordination Office (NNCO), university and industrial nanotechnology programs, and other stakeholder groups to develop a continuing stream of information to inform the public of the benefits and risks stemming from scientific and technological progress at the nanoscale. The rapid growth in information technologies is creating new interaction paradigms that might be exploited using electronic media such as Wikipedia, FaceBook, Second Life, YouTube, and Kindle [32].

## *4.4 College/University NSE Education*

The multidisciplinary/transdisciplinary nature of nanoscale science and engineering will continue to require center/institute type activity at colleges and universities. These centers/institutes should be widely dispersed geographically such that their facilities and capabilities are accessible to others without the need for extensive travel time. Further, introducing web-controlled instrumentation for remote access of selected instruments can potentially provide laboratory experiences for K–12 and community college students whose schools otherwise could not provide them.

Nanoscale science and engineering R&D will create many opportunities for innovative, disruptive technologies. Motivated, skilled entrepreneurs will be essential to carry the research discoveries into marketable technologies. College/university educators must find ways to nurture budding entrepreneurs. Models include the MIT Institute of Nanotechnologies "Soldier Design Competition" (http://web.mit.edu/isn/newsandevents/designcomp/finals.html), the University of South Carolina's "Ivory Tower to Marketplace: Entrepreneur Laboratory" (http://www.nano.sc.edu/news.aspx?article_id=27) and the University of Southern California Steven's Institute for Innovation's "Student Innovator Showcase and Competition" (http://stevens.usc.edu/studentinnovatorshowcase.php).

## *4.5 Community College NSE Education*

Many community colleges do not have the faculty, staff, and facilities resources to offer a meaningful nanotechnology education that includes exposure to state-of-the-art nanotechnology fabrication tools and, more importantly, to nanotechnology characterization tools. The model developed and supported by the NACK Center (see Sect. 8.3) uses resource-sharing among community colleges, research universities, and NACK to bring a meaningful nanotechnology education experience to 2-year degree students. This experience can include attending nanotechnology courses at the research university partner, using NACK web-available course materials, and using NACK equipment accessed via the web. The community colleges benefit by being able to give a state-of-the-art nanotechnology education; the research universities benefit by gaining access to a new source of potential students for 4-year degree programs.

## *4.6 K–12 NSE Education*

The growing knowledge base at the nanoscale, coupled with the importance of nano-enabled technology solutions to high-priority global challenges in renewable energy, energy conservation, potable water, heath, and environment, compel introduction of NSE into K–12 curricula. Funding is needed to allow for the design, development, testing, and implementation of a coherent curriculum that would allow 7- to 18-year-old students to develop an integrated understanding of core science ideas that underpin nanoscale science and engineering. Such a curriculum would focus on helping students develop progressively deeper understanding of core ideas. Such a process calls for changes in the standards that focus on teaching big ideas, with a focus on developing a deeper understanding of these ideas. In addition to the standards and curricula requirements, web-based materials addressing the nanoscale, vetted for accuracy and effectiveness, need to be created and presented in formats convenient to K–12 teachers and students. These materials must be correlated with United States and internationally benchmarked common core standards.

### *4.7 Global Partnerships in NSE Education*

There are numerous groups around the world addressing STEM education, nanoscale education, nanoscale science and engineering research, and nano-enabled technologies. There is an immediate challenge to integrate these various communities.

## 5 R&D Investment and Implementation Strategies

### *5.1 Facilities*

The impressive array of existing nanoscience R&D user facilities faces two key challenges: to provide sustained operating funds to support local expertise available to assist itinerant users, and to continually maintain/update the instrumentation. Nanocenters with unique, expensive instruments have been developed by many nations. As nanoscale science and engineering require more sophisticated systems, it is inevitable that new instrumentation will be expensive. Furthermore, the sensitivity of those instruments will require buildings engineered to adequately manage "noise" that can affect instrument results, i.e., fluctuations in temperature, pressure, cleanliness, electromagnetic radiation, vibration, acoustics, electrical power quality, etc.; those buildings will be expensive to build and operate. International and industrial partnerships will become more important as an approach to share the cost burden.[7] One example is the government-university-industry partnership that has created the College of Nanoscale Science and Engineering facility at the University of Albany, New York (see Sect. 8.5).

The NSF National Nanotechnology Infrastructure Network (NNIN), NSEC, DOE nanocenters, and the NIST Center for Nanoscale Science and Technology are working with the NSTA and the DoEd toward preparation of on-site and/or remote access to high-end user facilities that can contribute to the education process at various levels.

Some of the present centers, especially those with a manufacturing focus, could be morphed into user facilities that provide prototyping capabilities. However, to fully represent the breadth of need capability, it is likely additional user-facilities will need to be created.

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[7] Buildings for Advanced Technology", pending report from the NNI workshops in 2003, 2004 and 2006.

## 5.2 Federal Agency Investment in NSE Education

As has been noted in several places above, nanoscale science and engineering present numerous challenges to the K–Gray (i.e., continuing education for preschool through the senior years) education system. In the United States, the National Science Foundation has borne the major cost of developing nanoscale science and engineering education. As NSE leads to pervasive nano-enabled technologies, other agencies also must contribute toward the educational process. Table 2 illustrates education/training programs across the U.S. Federal government that should increase their participation in NSE educational efforts. That being said, as the prime agency responsible for STEM education, NSF must continue and expand its efforts as well.

The NSET, which has representation from 25 participating Federal agencies, should create a nanotechnology education and workforce working group to support agency efforts in addressing education and workforce issues. The working group should be guided by an education- and workforce-focused consultative board comprising the various principal stakeholders.

NSF's investments in cyberinfrastructure (e.g., [34]), along with those of other agencies, have resulted in a broad range of state-of-the-art, distributed digital resources, some for nanotechnology and science research, some for nanotechnology learning and education, and some for nanotechnology events and news. These cyber-nanotechnology resources vary in terms of their target audiences (education level, country of origin, original purpose), quality, level of integration with other

**Table 2** Federal education programs with potential for NSE content

| Agency | Program | URL |
|---|---|---|
| DOD | National defense education program | http://www.ndep.us/ |
| DOE | Energy education | http://www1.eere.energy.gov/education/ |
|  | National labs | http://www.energy.gov/morekidspages.htm |
| DoEd |  | http://www.ed.gov/index.jhtml |
| DOL | Training, continuing education | http://www.doleta.gov/ |
| DOT | Education and research | http://www.dot.gov/citizen_services/education_research/index.html |
| EPA | Teaching center | http://www.epa.gov/teachers/ |
| NASA | Education program | http://www.nasa.gov/offices/education/programs/index.html |
| NIH | Office of science education | http://science.education.nih.gov/home2.nsf/feature/index.htm |
| NIST | Educational activities | http://www.nist.gov/public_affairs/edguide.cfm |
| NOAA | Education resources | http://www.education.noaa.gov/ |
| NSF | Education & human resources | http://www.nsf.gov/funding/pgm_list.jsp?org=ehr |
| USDA | NRCS | http://soils.usda.gov/education/resources/k_12/ |
|  | AFSIC | http://www.nal.usda.gov/afsic/AFSIC_pubs/K–12.htm |
|  | NIFA (formerly CSREES) | http://www.agclassroom.org/ |

cyberinfrastructure resources, usage, and usage reporting. Most lack inclusion of meta-information, which may limit knowledge transfer across user communities in terms of discoverability, search ability, and adaptability. The emerging nanoscale education community must be able to exploit existing cyberinfrastructure resource investments more effectively.

## *5.3 Informal/Public NSE Education*

In the 2010–2015 time frame, it will be important to continue investment in the Nanoscale Informal Science Education Network (NISE Net) to promote informal public understanding of NSE. Goals should include achieving deeper sustainable impact on 100 institutions of informal education, broader reach across the range of organizations that engage in informal education, stronger connections to K–12 formal educational efforts, and greater inclusion of applications and societal perspectives in educator professional development and in the collection of educational materials.

Under the umbrella of broader impact requirements for center grants, there should continue to be strong encouragement by funding agencies of socially relevant educational outreach and public engagement activities, with encouragement to partner with informal science education organizations to generate these activities. Funding of research centers, and not only of small, individual research projects, is essential to realizing the critical mass necessary to make such collaborations productive. Research centers or research networks should be created and funded to address the grand challenges to society, span research at the nanoscale and at other scales of matter, provide specific funding for public participation in technology assessment and governance, and build an R&D agenda shared by the public, scientists, and policymakers. There will be an ongoing need to invest in educator training and materials development, with the goals of finding new ways to effectively communicate critical ideas about nanotechnology to the public, to keep abreast of new developments, and ensure that the educational momentum developed in the initial years of the NNI is well positioned to capitalize on public interest generated by future developments, whether they be positive breakthrough applications or events that raise concern.

The NNCO should take a more formative and supportive role in organizational and public relations related to nanotechnology developments, not to manage perceptions but to provide accurate and objective information in multiple public venues, using multiple platforms. Web communication must shift from passive web presences to active Web 2.0 efforts to engage highly relevant publics with nanoscience. Platforms like Facebook and Twitter are important mechanisms to communicate with the public in ways they are familiar with.

To date, the NISE Net has largely examined how “nano” fits into the size scale of materials, but a change of emphasis may be needed. Several studies have suggested that students will respond best to STEM in terms of addressing societal problems.

Now that nano-enabled technologies are beginning to proliferate, it would be timely to develop exhibits and programs associated with the impacts of those nano-enabled technologies.

NSF, which is the principal funding source for new nanoscale science and engineering projects, should take the lead in establishing links between museums and the national and international research communities for new exhibit and program development. Other stakeholders such as Federal funding agencies and industry representatives must also be contributors, since they will be engaged in the translational efforts that lead to technology impact.

## *5.4 College/University NSE Education*

In the second decade of the U.S. National Nanotechnology Initiative there will be growing emphasis on transitioning science discovery into innovative technology. Industry involvement will be crucial. The NSF Engineering Research Centers already require partnerships with industry; any new NSF Center competitions focused on the nanoscale should incorporate industrial partners to foster innovation and workforce development. The NSF Grant Opportunities for Academic Liaison with Industry (GOALI) and Industry & University Cooperative Research Centers (I/UCRC; http://www.nsf.gov/eng/iip/iucrc/) programs should be exploited to a greater degree. Further, industry can provide its own incentives to colleges/universities through partnerships such as the Semiconductor Research Council Education Alliance (http://www.src.org/alliance/), Hewlett Packard Lab's Open Innovation Office (http://www.hpl.hp.com/open_innovation/), IBM's University Research & Collaboration (https://www.ibm.com/developerworks/university/research/), and the ASEE/NSF Corporate Research Postdoctoral Fellowship for Engineers (https://aseensfip.asee.org/jobs/57).

## *5.5 Community College NSE Education*

NSF, DoEd, and other agencies with relevant missions should foster development and evaluation of nanotechnology curricula appropriate for community colleges, and ensure meaningful collaborations between the community colleges and the nanocenters. The DoEd's Department of College and Career Transitions program should ensure nanotechnology is included in that program.

To address the facilities issue, state governments, working in concert with the DoEd and local industries, need to develop mechanisms to enable interactions between the research universities, national laboratory facilities, and community colleges. Some states are taking steps and making good progress toward that integration: Texas has established the Texas Nanotechnology Workforce Development Initiative (http://nanotechworkforce.com/resources/workforce.php), and Pennsylvania has established the Center for Nanotechnology Education and Utilization (http://www.cneu.psu.edu/abHomeOf.html). One solution is integrating community college courses with nearby research universities, where they are available.

### 5.6 K–12 NSE Education

Without incorporating the current understanding of nanoscale science and engineering into science and engineering learning standards in each of the states, action at the K–12 levels of education will be minimal, and increasing nanoscience literacy toward a productive workforce will be inadequate. The NSE community, encouraged and funded by NSF and DoEd, must work with the National Governors Association and the Council of Chief State School Officers on the internationally benchmarked common core standards.

There will be growing inclusion of nanoscale science, engineering, and technology into standards of learning. The NSE community, encouraged and funded by NSF and DoEd, must work with the NSTA, professional science and engineering societies, and other pertinent organizations (including ones with international perspectives) to develop curricula, learning resources, and teacher training.

### 5.7 Global Partnerships in NSE Education

A focal international activity is needed to identify, validate, and integrate the many nanoscale education capabilities that presently exist around the world and to assess what is still needed.

## 6 Conclusions and Priorities

### 6.1 Facilities

- The nanoscale research facilities at centers and user-facilities currently are well equipped, but nanoscale science, engineering and technology is changing rapidly; it will be a challenge to keep those facilities to-to-date. There must be continued attention paid to facility infrastructure so as to sustain operation costs and the availability of local expertise. Periodic updates of instrumentation will be necessary, with careful consideration to most effective use of funds (i.e., no unwarranted duplication). Partnerships between countries, industries, and universities will be needed to sustain the funding for needed capabilities. Continued

> NSF support for centers addressing the nanoscale is essential, since the funding necessary to acquire and sustain measurement/fabrication facilities can only be obtained through center-level efforts.

In addition, some of the present centers, especially those with a manufacturing focus, should be morphed into user facilities that provide prototyping capabilities. To fully represent the breadth of need manufacturing/prototyping capability, it will likely be necessary to create some additional user-facilities.

The U.S. investment in nanotechnology education has spawned a new paradigm for STEM education, which if broadly implemented, will allow the United States to maintain its global leadership in science and technology. This new paradigm is based on three types of integration – horizontal, vertical, and system – that can drastically improve student learning and significantly save education costs:

- *Horizontal integration* proceeds from the unique fusion of physical and biological properties of matter that exists at the nanoscale together with engineering design. Teaching this fusion has shown that eliminating traditional distinctions between STEM disciplines can produce deeper and broader student understanding. Exposure to cross-cutting ideas helps students learn to synthesize concepts from diverse sources and apply them to new situations. Integration with social and business sciences offers social relevance.
- *Vertical integration* means providing sustained, high-quality educational opportunities from precollege to graduate levels. Early exposure and consistent reinforcement saves time and minimizes redundancy and misconceptions. New discoveries can be rapidly transferred from the laboratory to the classroom through the participation of university researchers in developing precollege course content and in training teachers.
- *System integration* bridges the gap between basic science and engineering concepts and their applications. Hands-on design challenges build student confidence and emphasize critical thinking and innovation – key skills for a globally competitive workforce.

Although these principles will vastly improve the overall quality and effectiveness of national STEM education, it is important that NSE education should also be a focus. Discoveries and inventions at the nanoscale are driving technological progress and have become essential to economic development and global welfare. Our students must be prepared as nano-literate workers, consumers, and citizens

Partnership is emphasized for these activities because those interested in NSE education believe it is time to: (a) broaden the education efforts to explicitly include the many stakeholder communities; (b) establish a more enduring infrastructure than just the periodic Nanoscale Science and Engineering Education workshops (held in 2006, 2007, and 2008); and (c) develop partnerships to meet the challenges and identify the opportunities provided by the global advances at the nanoscale. This is consistent with the Carnegie Opportunity Equation report [27] that calls for a national mobilization in education exploiting partnerships.

Specific items for attention include:

- Internationally benchmarked standards must be created for the inclusion of nanoscale science and engineering in K–12 education. Since NSE is still rapidly evolving, those standards must be periodically vetted for currency.
- Curricula incorporating nanoscale science and engineering, and correlated to the standards, must be created, vetted by the teaching communities, and made readily available. Web-based and other electronic media must be utilized to better connect with new students who are growing up with those information media.
- Establish a network of regional hub sites – the Nanotechnology Education Hub Network – as a sustainable infrastructure for accelerating nanotechnology education. The hub sites would allow for efficient regional and national field-testing of new content and methodologies.
- There are numerous groups around the world addressing STEM education, NSE education, nanoscale science and engineering research, and nano-enabled technologies. There is an immediate challenge to integrate these various communities. There is a need to identify, validate, and integrate the many NSE educational capabilities that presently exist and to assess what is still needed.
- The NSET should create a working group on nanotechnology education and workforce to support agency efforts to address education and workforce issues. An education and workforce-focused consultative board to the NSET should also be created, comprising the various principal stakeholders. NNCO funds (or other contributions from the various Federal NNI agencies) should be used for this effort
- Consideration should be given to the research and development of an overall mechanism for efficient search, access, and use of cyber-infrastructure resources focused on nanoscience and nanotechnology; this has potential relevance to education at all levels. Such a mechanism would likely entail creating an inventoried, analyzed, tagged registry. Also worth considering are mechanisms for enabling greater interoperability with emerging cyber-nanotechnology resources such as remote access to and control of state-of-the-art nanotechnology characterization equipment; databases for properties and applications; environmental, health, and safety implications and best practices; and general educational paradigms, such as virtual and immersive environments, simulations, and games. Such integration and knowledge-sharing offer great promise for accelerated discovery and learning.
- The DoEd, working closely with the NSTA and cyber-oriented curriculum developers (such as those listed in Murday [7], Table 6), should create a core resource website for information and activities in support of NSE education. The NSTA should serve as the evaluator or resource for quality control to ensure the materials of NSE-focused educational websites are of high quality, are in a format readily utilized by K–12 teachers, are carefully indexed to the various state learning standards, and can be readily accessed from the NSTA website.

Additional well-designed, highly interactive, media-rich, online learning tools should continue to be developed.

- There must be a close and continuing dialogue between industry and the education communities so that education standards and curricula adequately reflect workforce needs.
- Public concern over environmental safety and health issues at the nanoscale compels attention to both the formal and informal education processes. Workers and members of the general public may be in contact with nanomaterials in various forms during manufacture or in products and should be sufficiently knowledgeable to understand both benefits and risks.
- NSF, DoEd, and other agencies with relevant missions should foster nanotechnology curricula development and evaluation that is appropriate for community colleges and ensure meaningful collaborations between the community colleges and the nanocenters. The DoEd's Department of College and Career Transitions program addressing articulation should ensure nanotechnology is included in that program.
- The NSF National Nanotechnology Infrastructure Network (NNIN), NSEC, DOE nanocenters, and the NIST Center for Nanoscale Science and Technology should work with the NSTA and the DoEd to facilitate on-site and/or remote access to the higher-end user facilities that might contribute to K–12 STEM education.
- Wikipedia is becoming the de facto global encyclopedia. Current entries addressing nanoscale science and engineering in Wikipedia are woefully inadequate and must be routinely updated, expanded, vetted, and sustained.

While all of the items above have merit, higher priority should be given to:

- Incorporation of nanoscale science and engineering knowledge into education at all levels, but especially in the K-12 grades where all citizenry can be informed of the growing knowledge and its technological implications. The development of internationally benchmarked standards for the role of the nanoscale in K-12 education is critical; without those standards other priorities may preclude adequate attention to the nanoscale.
- The development of user facilities to provide prototyping capabilities. Without facilitating the transition of science/engineering discovery into innovative technologies, continued support for nanoscale science and engineering could be jeopardized.
- Establish a sustainable National Nanotechnology Education Hub Network for accelerating NSE/STEM education at all levels through content/learning tool development, teacher/workforce training, and informal education programs.
- Reflecting the growing use of electronic media, both formal and informal education in nanoscale science, engineering and technology needs to better exploit high-quality, web-accessible content. Further, user-friendly web-based remote control of facility analytical and fabrication tools are needed to make those capabilities more broadly available.

## 7 Broader Implications for Society

Education and physical infrastructure development are enabling conditions for realizing the promise of nano-enabled technology solutions expected to impact many of the pressing societal problems. Further, the excitement associated with addressing those problems may redress the lack of interest in science and engineering careers for native students in developed countries.

## 8 Examples of Achievements and Paradigm Shifts

### *8.1 NCLT: Establishing a Nanotechnology Academy as a Small Learning Community in a Los Angeles Unified School District High School (http://www.nclt.us/)*

*Contact person*: Robert Chang, National Center for Learning and Teaching in Nanoscale Science and Engineering (NCLT)

NCLT has spearheaded the development of a model to systematically introduce nanoscience curriculum into secondary education in the United States. The goal is to create a more concentrated learning environment with a focus on nanotechnology by adopting the Small Learning Community (SLC) program already existing in some high schools. The SLC concept was developed by DoEd in response to today's "knowledge-based" economy as a means to increase students' literacy, analytic, and mathematical skills so they can be more successful in postsecondary education or the workforce. These SLCs are, in essence, schools within schools. Each forms a smaller learning cluster that is separate, autonomous, and distinct as a sub-school unit. These smaller school units often have advantages over the larger schools, especially because they make it easier to focus on more personalized teaching and learning, such as on the theme of nanotechnology.

NCLT has partner with Los Angeles Unified School District's (LAUSD) Taft High School to create a pilot nanotechnology SLC during the 2009–2010 school year. The goal is to help students in the SLC to obtain a strong set of core skills in nanoscience and nanotechnology. NCLT created a 15-min promotional DVD for Taft to be able to "market" its newly created Nanotechnology Academy during spring student recruitment. Taft teachers held orientation meetings with students and parents at feeder schools, where they distributed Nano Academy brochures and discussed Academy goals. To further heighten student interest in nanotechnology, NCLT provided a Nano-Tex™ lab coat to one of the science teachers. During a lunch recess, the teacher demonstrated the fabric's nanostructure-based nonstaining properties by allowing students to throw staining liquids on the pristine white lab coat; they were amazed at how nanotechnology could prevent staining on the coat. In another promotional activity, NCLT designed a contest for several science classes to use nanotechnology concepts to maximize a geyser erupting from a carbonated drink. After several weeks of classroom experimentation, the contest was promoted as a school-wide event. The recruiting goal for the Nano Academy is to serve 120 ninth and tenth grade students in the first year and continue to grow in succeeding years to include grades 9 through 12 and eventually to serve about 350 students per year.

Working closely with target Academy teachers who participated in a 2-week nanotechnology summer workshop at Northwestern, NCLT developed a course syllabus for the Academy's introductory courses on nanotechnology during the 2009–2010 implementation. The Academy plans to offer two classes in the first year: Intro to Nano (for grades 9–10) and Nano Tech (for grades 10–12). NCLT continues to work closely with Los Angeles high school teachers to:

- Develop a 4-year nanotechnology-based curriculum
- Develop cross-cutting nanotechnology projects
- Develop essential and guiding questions for use in English, Social Sciences, and other SLC classes, leading to fully interdisciplinary curricula and resource materials
- Carry out professional development for SLC teachers and train a cadre of lead SLC teachers
- Assist the SLCs in building strong partnerships with area universities (e.g., University of California Los Angeles, University of Southern California, and California State University Northridge), industry (Boeing's JRL Laboratories and General Motors), technical societies, etc.
- Collaborate with LAUSD to develop an evaluation plan to assess student achievement levels

## *8.2 Informal Education: NISE Net's NanoDays (http://www.nisenet.org/nanodays)*

*Contact person*: Larry Bell, Museum of Science, Boston

Organized by the Nanoscale Informal Science Education Network (NISE Net), science museums and research centers have worked together to present NanoDays activities at over 200 sites across the nation during a week each spring from 2008 to 2010 to help inform the public about nanoscale science, engineering, and technology in exciting, creative, hands-on ways. NISE Net is funded by a cooperative agreement with the National Science Foundation's Division of Research on Learning in Formal and Informal Settings and led by the Museum of Science in Boston, the Science Museum of Minnesota in St. Paul, and the Exploratorium in San Francisco.

Informal educational activities about nanoscale science and engineering were virtually nonexistent 10 years ago, and even fundamental ideas about the behavior of matter at the nanoscale were mostly absent from informal science education.

For the most part, informal science educators felt that content of this sort was too difficult for the public to understand, not really exhibitable, and of little interest. As a result, prior to 2005, nanotechnology was covered in only a small number of institutions of informal science education. Inverness Research Associates (2009) reported that at that time there was little expertise, experience, or incentive to do nanoscale science education for the public. Neither science museums nor science research institutions had all the requisite capacities to carry out high-quality nanoscale science education, and they found little incentive to develop such capacity, as it was unclear that their audiences had a driving interest in the topic. Today, hundreds of informal educational institutions, many working in collaboration with university research centers, have introduced activities about nanoscale science and technology into their educational programs. Inverness has found (2009) that national NISE Net efforts in the last part of the decade, in particular NanoDays, have been catalytic in engaging new informal science education institutions and scientists to enter into nanoscale science education. The first NanoDays event in April 2008 had approximately 100 institutional participants; the second and third events in April 2009 and April 2010 each had approximately 200 institutional participants (Fig. 5).

NanoDays has not only introduced science museums to hands-on activities related to nanotechnology but also has created collaborations between science museums and nanoscale research centers. The public has benefited from the knowledge and expertise shared by researchers and graduate students, and students have gained valuable experience in communicating with the public about their areas of research.

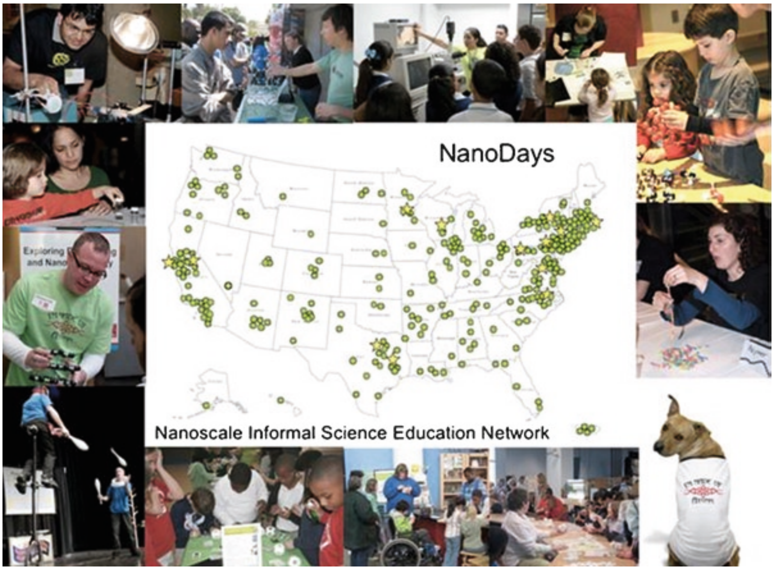

**Fig. 5** NanoDays map showing the distribution of NanoDays kits to over 200 sites in all 50 states, Washington, DC, and Puerto Rico, with photographs of some of the wide range of activities that have taken place across the nation (Courtesy of L. Bell)

## *8.3 Pennsylvania State University Center for Nanotechnology Education and Utilization (http://www.nano4me.org/index.html)*

*Contact person*: Steve Fonash, Pennsylvania State University

The Pennsylvania State University (Penn State) Center for Nanotechnology Education and Utilization is the research university partner to the Pennsylvania community and technical colleges. Through a resource-sharing partnership entitled the Pennsylvania Nanofabrication Manufacturing Technology (NMT) program, 27 academic institutions in Pennsylvania are able to offer a total of 54 two-year and four-year nanotechnology degrees [35]. The students in all of these programs must spend one semester at Penn State attending the hands-on nanotechnology fabrication, synthesis, and characterization immersion provided by the Capstone Semester, a six-course hands-on experience exposing students to state-of-the art equipment and clean room facilities (Fig. 6). The 18 credits of coursework can be used toward an associate or baccalaureate degree, used to earn an NMT Certificate, or both, depending on the specific program of the student's home institution. Refinement of the capstone semester is carried out in close consultation with the industry members of the NMT program's advisory board.

NSF, with contributions from the Penn State University Center for Nanotechnology Education and Utilization, supports the National Nanotechnology Applications and Career Knowledge Center. NACK addresses the widespread need for a workforce possessing strong nano- and microtechnology 2-year degrees [36]. NACK leadership also believes that bringing a nanotechnology education to 2-year degree institutions and exposing students attending these institutions to this exciting field is a motivating force that can bring a new demographic to 4-year STEM degree programs and beyond.

**Fig. 6** NACK's laboratory practice as part of the NMT Capstone Semester (Courtesy of S. Fonash)

NACK has introduced a number of paradigm shifts designed to give the United States a well-trained nano- and micro-technology workforce. These shifts address four key issues faced by many community and technical colleges as they consider developing nanotechnology programs:

- *Economic pressures*. To alleviate the economic burden of creating and sustaining four semesters of new courses, NACK has introduced the concept of a capstone semester (as described above for the NMT program). The capstone semester consists of a suite of courses designed to give students from various science and technical programs (e.g., biology, engineering technology, chemistry, and physics) an immersion experience in nanotechnology. There is a skill set requirement rather than a course set requirement for entry into the capstone semester. The entry skill set requirements can be met by traditional biology, chemistry, engineering technology, math, materials science, and/or physics courses available at most 2-year institutions. Institutions thus do not need to develop four semesters of new courses. Students emerge from the NMT capstone semester with an exit skill set developed by the NACK Industry Advisory Board.
- *Student enrollment pressures*. The nanoscience capstone semester approach eliminates the pressure to maintain a baseline student enrollment in a high-tech program. Students move from traditional programs into the nanotechnology immersion capstone semester provided by a university. The critical mass of students needed to economically maintain a nanotechnology education experience only must be attained by the university for the capstone semester.
- *Pressures on faculty, staff, and facilities resources*. The NACK approach to the faculty, staff, and facilities issues faced by 2-year degree-granting institutions is one based on resource sharing. It entails several components: (1) sharing facilities and (2) sharing courses. Sharing facilities means 2-year-degree students using the facilities at a research university to obtain hands-on nanotechnology exposure, or it means community colleges themselves setting-up a teaching clean room facility to be shared among institutions in a given area. In the NACK approach, sharing courses has the following possible implementations: a research university assuming responsibility for teaching the capstone semester for students attending from community colleges, community college students using web-accessible courses provided by NACK, and community college faculty using units from NACK's web-accessible courses.
- *Geographic isolation of some 2-year degree institutions*. The NACK approach to overcoming the drawbacks of geographic isolation in teaching students interested in nanotechnology is two-fold: offering the capstone semester courses online for downloading, and providing web-based access to equipment. The NACK philosophy is that it is best to operate a tool (field-emission scanning electron microscope, scanning probe microscope, etc.) using a computer right next to it, but second-best is to operate the tool with a computer via the web.

## 8.4 Network for Computational Nanotechnology (http://www.ncn.purdue.edu/home/; http://nanohub.org/)

*Contact person*: George Adams, Network for Computational Nanotechnology

The Network for Computational Nanotechnology (NCN) supports the National Nanotechnology Initiative by designing, constructing, deploying, and operating the nanoHUB.org national cyber-infrastructure for nanotechnology theory, modeling, and simulation. NCN was established in September 2002 and is funded by the National Science Foundation to support the NNI.

Powered by the HUBzero.org platform created at Purdue University and released as open source software on April 14, 2010, nanoHUB.org is a science gateway where users can run any of over 170 nanotechnology simulation programs using their web browsers with just the click of a button. In the 12 months prior to May 2010, nanoHUB users ran 340,000 such simulations (see map of U.S. users, Fig. 7). They also learned about nanotechnology from 2,100 educational resources, including state-of-the-art seminars and complete courses authored by over 660 members of the nanotechnology research and education community.

The nanoHUB software has already had a strong impact on U.S. NSE education. The simulations and resources of nanoHUB have directly supported 575 research papers in the nanotechnology literature to date. In 2009, faculty at 76 universities used nanoHUB in 116 classes, including all top 50 U.S. engineering schools and 88% of the top 33 physics and chemistry schools. It should be noted that nanoHUB is reaching students at all academic levels, and it has assumed a strong role in the science education of minority and nontraditional students. It is used at 25% of the

**Fig. 7** Users of the National Nanotechnology Network in the United States

256 U.S. minority-serving institutions with STEM discipline degree programs, at 32% of Historically Black Colleges and Universities, and at 39% of institutions with high Hispanic enrollment. Bruce Barker, President of Chippewa Valley Technical College, Eau Claire, Wisconsin, has pointed to nanoHUB's value to his students, "We have a high percentage of non-traditional students, many of whom are older and starting new careers, or who are coming from disadvantaged families; nanoHUB provides them with a toe-hold to a wider academic world." (from telephone interview Jan. 2010; courtesy of G.B. Adams).

NCN is leading an effort to rethink electronic devices from the nanoscale perspective. With support from Intel Foundation, NCN has created "Electronics from the Bottom Up," courseware that may reshape the teaching of nanoelectronic technology and will train a new generation of engineers to lead the twenty-first Century semiconductor industry. Using these new concepts, NCN is building an electronic device simulation platform that powers several tools on nanoHUB and runs efficiently on the largest computers on the national grid. Recent achievements include modeling the effect of a single donor atom in the active region of a FinFET nanotransistor [37]. Dr. Dmitri E. Nikonov, Components Research, Technology, and Manufacturing Group, Intel Corporation, who is charged with using simulation to evaluate beyond-CMOS electronic devices (the next generation of transistors), asserts that, "nanoHUB tools are indispensible to the mission of my department."

## *8.5 University of Albany, College of Nanoscale Science and Engineering (http://cnse.albany.edu/)*

*Contact person*: Alain Diebold, University of Albany, State University of New York (SUNY)

The College of Nanoscale Science and Engineering (CNSE) of the University at Albany, State University of New York (SUNY), is the first college in the world dedicated to education, research, development, and deployment in the emerging disciplines of nanoscience, nanoengineering, nanobioscience, and nanoeconomics. At CNSE, academia, industry, and government have joined forces to advance atomic-scale knowledge, educate the next-generation workforce, and spearhead economic development. The result is an academic and corporate complex that's home to world-class intellectual capital, unmatched physical resources, and limitless opportunities.

CNSE has reshaped the traditional "silo" type college departmental structure into four cross-disciplinary constellations of scholarly excellence in nanoscience, nanoengineering, nanobioscience, and nanoeconomics. Through this game-changing paradigm, students engage in unique hands-on education, research, and training in the design, fabrication, and integration of nanoscale devices, structures, and systems to enable a wide range of emerging nanotechnologies. Students are supported by internships, fellowships, and scholarships provided by CNSE and its array of global corporate partners. CNSE complements its groundbreaking bachelor's, master's and PhD programs in nanoscale science and engineering with educational outreach to elementary, middle, and high schools; partnerships with community colleges and academic institutions around the world; and certificate-level technical training. This unprecedented effort is designed to educate the next generation of nanotechnology-savvy professionals and build the foundations of a skilled nanotechnology workforce at every level.

The setting for this pioneering research and educational blueprint is CNSE's world-class Albany NanoTech Complex (Fig. 8), the most advanced research enterprise of its kind anywhere in the world. This 800,000-square-foot megaplex has attracted more than $6 billion in public and private investment and houses the only fully-integrated, 300 mm wafer, computer chip pilot prototyping and demonstration line within 80,000 square feet of Class 1–capable clean rooms. Over 2,500 scientists, researchers, engineers, students, and faculty work at CNSE's Albany NanoTech Complex, which serves as a primary research and development location for a host of leading global high-tech corporations co-located on-site, including IBM, AMD, GlobalFoundries, International SEMATECH, Tokyo Electron, Applied Materials, ASML, Novellus Systems, Vistec Lithography, Atotech, and many more. An expansion currently in the planning stages is projected to increase the size of the CNSE Albany NanoTech Complex to over 1,250,000 square feet of state-of-the-art infrastructure, housing over 105,000 square feet of Class 1–capable clean rooms. Once completed, the expanded CNSE Albany NanoTech Complex is expected to house over 3,750 scientists, researchers, and engineers from CNSE and global corporations.

Buoyed by its unparalleled combination of intellectual know-how and leading-edge technological infrastructure, CNSE's Albany NanoTech Complex is the site of some of the world's most advanced nanoscale research, development, and commercialization activities. Here, academic and corporate scientists engage in innovative research in a variety of fields, including clean energy and advanced sensor and environmental technologies; advanced CMOS and post-CMOS nanoelectronics; 3D integrated circuits and advanced chip packaging; ultra-high-resolution optical, electron, and EUV lithography; and nanobioscience and nanomedicine. The result is a vibrant and powerful entity that is driving critical innovations to address the most important challenge areas facing society, from energy, the environment, and health care to military, telecommunications, information technology, and transportation, among many others.

**Fig. 8** Photos of the Albany NanoTech Complex and labs (Courtesy of A. Diebold)

## *8.6 DOE Nanoscale Science Research Centers (http://www.nano.energy.gov)*

*Contact person*: Altaf Carim, Department of Energy Office of Basic Energy Sciences

There are five DOE Office of Science Nanoscale Science Research Centers (NSRCs), as follows:

- Molecular Foundry – Lawrence Berkeley National Laboratory (California)
- Center for Nanoscale Materials – Argonne National Laboratory (Illinois)
- Center for Functional Nanomaterials – Brookhaven National Laboratory (New York)
- Center for Integrated Nanotechnologies – Los Alamos National Laboratory and Sandia National Laboratory (New Mexico)
- Center for Nanophase Materials Sciences – Oak Ridge National Laboratory (Tennessee)

Taken together, these centers provide resources unmatched in the world. The new nanocenter buildings contain clean rooms, laboratories for nanofabrication, one-of-a-kind signature instruments, and other instruments (such as nanopatterning tools and proximal probe microscopes) not generally available except at major scientific user facilities. These facilities are designed to be the nation's premier user centers for interdisciplinary research at the nanoscale, serving as the basis for a national/international program that encompasses new science, new tools, and new computing capabilities.

Each center is housed in a new laboratory building near one or more existing DOE facilities for x-ray, neutron, or electron scattering to take advantage of their complementary capabilities; those facilities include the Spallation Neutron Source at Oak Ridge; the synchrotron light sources at Argonne, Brookhaven, and Lawrence Berkeley; and semiconductor, microelectronics and combustion research facilities at Sandia and Los Alamos. Each center has particular strengths in different areas of nanoscale research, such as materials derived from or inspired by nature; hard and crystalline materials, including the structure of macromolecules; magnetic and soft materials, including polymers and ordered structures in fluids; and nanotechnology integration. User access to center facilities is through submission of proposals that are reviewed by independent proposal evaluation boards.

## *8.7 NIST Center for Nanoscale Science and Technology (http://www.nist.gov/cnst/)*

*Contact person*: Robert Celotta, NIST CNST

The Center for Nanoscale Science and Technology (CNST) at the National Institute of Standards and Technology was established in May 2007 to accelerate innovation in nanotechnology-based commerce. It supports the development of nanotechnology through research on measurement and fabrication methods and technology. The CNST has a unique design that supports the U.S. nanotechnology enterprise through the readily available, shared-use NanoFab facility, as well as by providing opportunities for collaboration in multidisciplinary research on new nanoscale measurement methods and instruments, which are housed in buildings designed to provide stringent environmental controls on particulate matter, temperature, humidity, vibration, and electromagnetic interferences. It also serves as a hub linking the international nanotechnology community to the comprehensive measurement expertise available throughout NIST.

The NanoFab is accessible to industry, academia, and government agencies on a cost-reimbursable basis, providing researchers economical access to and training on the advanced tool set required for cutting-edge nanotechnology development. The NanoFab provides a comprehensive suite of tools and processes for nanofabrication and measurement. It includes a large, dedicated clean room – with all the tools operated within an 8,000 Sq.Ft (750 $m^2$) Class-100 space – and additional tools in adjacent, high-quality laboratory space. Over 65 major tools are available for e-beam lithography, photolithography, nanoimprint lithography, metal deposition, plasma etching, atomic layer deposition, chemical vapor diffusion, wet chemistry, and silicon micro- and nanomachining. The facility is accessible through a straightforward application process designed to get users into the clean room in a few weeks.

CNST research is creating the next generation of nanoscale measurement instruments and fabrication methods, which are made available through collaboration with its multidisciplinary scientists and engineers. This research is agile and highly interactive by design, with significant contributions from a rotating cadre of post-doctoral researchers, and with many collaborative projects involving both NIST scientists and others in the United States and abroad. The CNST is currently giving priority to the following three research areas:

- *Future electronics*. In support of continued growth in the electronics industry beyond CMOS technology, the CNST is developing new methods to create and characterize devices, architectures, and interconnects for graphene, nanophotonic, nanoplasmonic, spintronic, and other future electronic devices.
- *Nanofabrication and nanomanufacturing*. The center is advancing the state of the art in nanomanufacturing by developing measurement and fabrication tools for both lithographic (“top-down”) and directed assembly (“bottom-up”) approaches.
- *Energy storage, transport, and conversion*. This research is focused on creating new methods for elucidating light–matter interaction, charge and energy transfer processes, catalytic activity, and interfacial structure at the nanoscale in energy-related devices.

## 8.8 National Nanotechnology Infrastructure Network (http://www.nnin.org/)

*Contact person*: Sandip Tiwari, National Nanotechnology Infrastructure Network

The National Nanotechnology Infrastructure Network (NNIN) is a collective of 14 university-based facilities with the mission to enable rapid advancements in nanoscale science, technology, and engineering through open and efficient access for fabrication purposes. Its facilities-based infrastructure resources are openly accessible to the nation's students, scientists, and engineers who come from academia, small and large companies, national laboratories, etc., providing the capacity to translate ideas to practice across disciplines and new frontier areas. NNIN also supports experimental efforts and an independent interdisciplinary theoretical effort through computational resources, where the emphasis is on modeling and simulation of advanced scientific problems of the nanoscale via open and tested software, hardware, and basis information. NNIN leverages its infrastructure resources and geographic and institutional diversity to conduct other activities with broader impact: in education, in enhancing diversity in technical disciplines, in societal and ethical implications of nanotechnology, and in health and environment efforts. Figure 9 shows the member institutions of NNIN.

NNIN serves the world's largest community of experimental graduate students, engineers, and scientists under one umbrella. During 2009–2010, NNIN resources were used by over 5,300 unique users for a significant part of their experimental work. Of these, over 4,000 were graduate students, about 800 were industrial users, and the rest were from U.S. state and Federal laboratories and foreign institutions. More than 300 small companies used NNIN facilities. Nearly 3,200 publications, several of them the significant scientific and engineering highlights of the year, resulted from the work of the user community. Nearly a quarter of PhD awards in "nano"-related disciplines utilized NNIN resources. Over 10% of the professionals of small companies supported through SBIR grants also utilized NNIN resources.

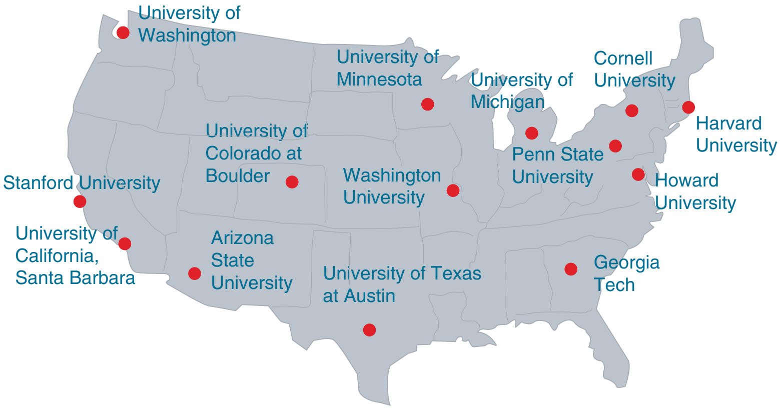

**Fig. 9** NNIN sites (Source: http://www.nnin.org)

Taken together, these figures show that NNIN is a major national force in human resource development and in R&D and commercialization of nanotechnology.

NNIN also has a broad portfolio in education and outreach. Its programs include (a) Research Experience for Undergraduates (REU); (b) International Research Experience for Undergraduates (iREU); (c) Laboratory Experience for Faculty (LEF); (c) Showcase for Students; (d) international Winter School for Graduate Students (iWSG); (e) Symposia; (f) *Nanooze* (a magazine for elementary and middle school students); (f) Open Textbook; and (g) technical workshops & symposia. Local activities from NNIN include day and longer camps for middle and high school students, local outreach through workshops for teachers, school and community-connected activities, and from Howard University, a laboratory on wheels that brings nanotechnology activities to high schools in the eastern part of the country.

NNIN's research efforts also include examination and development of (a) understanding of interdisciplinary collaborations and their impact on research, (b) the impact on competitiveness and the process of technology transfer and industrial innovation and innovation by industry through NNIN, (c) impact of government-funded faculty research and the faculty's interaction with industry in technology transfer, (d) impact of intellectual exchange, openness, and sharing such as in a network in conduct and impact of research, and (e) the ethical issues related to nanotechnology and fostering of ethical conduct.

Throughout the breadth of its network activities, NNIN seeks the integration and development of consciousness about social and ethical issues (SEI) related to nanoscience while being the nation's leading open-access scientific research facility. SEI efforts within NNIN therefore embody both the network's research and educational pursuits. NNIN has organized its SEI efforts to take advantage of the network's unique strengths as a national resource with geographic diversity, technical breadth, and community interests. Within its user community, NNIN provides training and educational opportunities through SEI modules and teaching materials employed in training and ongoing educational programs, selective incorporation of these in the network educational activities (REU, RET, workshops, symposia, etc.), and in broader outreach activities. NNIN provides opportunities for national researchers via competitive travel and seed grants to support related SEI investigations. NNIN stimulates and facilitates SEI research on the network's unique, world-leading strength – the largest collection of nanotechnology users (students and professionals), communities (academe and industry), and relevant technologies.

## *8.9 Nanotechnology Characterization Laboratory (http://ncl.cancer.gov/)*

*Contact person*: Scott McNeil, NCL

The Nanotechnology Characterization Laboratory (NCL) was established as an interagency collaboration among the National Cancer Institute (NCI), the National Institute of Standards and Technology (NIST), and the U.S. Food and Drug

Administration (FDA) to evaluate the safety and efficacy of biomedical nanomaterials. The NCL is a national resource for all nanotechnology researchers and helps facilitate the regulatory review process by conducting preclinical characterization using standard methods. By providing critical infrastructure and characterization services to nanomaterial providers, the NCL accelerates the transition of nanoscale particles and devices into clinical applications. The NCL's activities are markedly speeding the development of nanotechnology-based products, reducing associated risks, and encouraging private sector investment in this promising area of technology development.

Candidates for NCL characterization are selected through an application process, and characterization of accepted nanomaterials is provided at no cost to the submitting investigator. As part of its standardized assay cascade, the NCL characterizes the nanomaterial's physicochemical characteristics, its in vitro immunological and toxicological properties, and its in vivo compatibility using animal models. The time required to characterize a nanomaterial from receipt through the in vivo phase is 1 year or more. Data derived from the NCL assay cascade are intended to be included in an investigator-led filing of an Investigational New Drug (IND) or Investigational Device Exemption (IDE) with the FDA but also can be used in scientific publications or for promotion purposes (e.g., to garner investment). The NCL website provides more information on the NCL application process or the NCL Assay Cascade.

In addition to characterization of applicant-provided nanomaterials, the NCL also collaborates with several other government agencies, including the FDA's National Center for Toxicological Research (NCTR), the National Institute of Allergy and Infectious Disease (NIAID), and the National Institute of Environmental Health Sciences (NIEHS) to characterize nanoparticles for other applications, such as evaluation of environmental, health, and safety concerns. These agencies have come together to promote knowledge and data sharing and to coordinate research efforts on the potential risks of nanotechnology in medicine and the environment.

## *8.10 Three National Institutes of Health (NIH) Nanotechnology-Related Networks*

*Contact person*: Jeff Schloss, NIH, National Human Genome Research Institute

### 8.10.1 National Cancer Institute (NCI), Alliance for Nanotechnology in Cancer (http://nano.cancer.gov/)

*Contact person*: Piotr Grodzinski, NIH/NCI

The National Cancer Institute launched its Alliance for Nanotechnology in Cancer in 2004 to fund and to coordinate research that seeks to apply advances in nanotechnology to the detection, diagnosis, and treatment of cancer. The program is highly translational and focuses on techniques capable of producing clinically useful procedures. The Alliance builds on the premise of multidisciplinary research, engaging technology developers: chemists, engineers, and physicists, as well as biologists and clinicians – the community capable of identifying the most pressing needs of clinical oncology that are not met with currently available approaches. The Alliance operates as an integrated constellation of Centers for Cancer Nanotechnology Excellence (CCNEs) and smaller collaborative Cancer Nanotechnology Platform Partnerships (CNPPs), together with the Multidisciplinary Research Training awards and the National Characterization Laboratory (NCL). NCL, which is a collaborative effort with NIST and FDA, has become a national resource for nanomaterials characterization and developed an extensive cascade of assays to evaluate physical properties of nanostructures and their behavior in in vitro and in vivo environments.

Three challenge areas for the implementation of nanotechnologies into cancer research and oncology are:

- *Early diagnosis using in vitro assays and devices or in vivo imaging techniques*. Novel nanotechnologies can complement and augment existing genomic and proteomic techniques to analyze variations across different tumor types, thus offering the potential to recognize early the onset of the disease with sensitivity and specificity, which is not currently possible. Sensitive biosensors constructed of nanoscale components (e.g., nanocantilevers, nanowires, and nanochannels) can recognize genetic and molecular events and have reporting capabilities. The imaging contrast agents based on nanotechnologies (e.g., optical, magnetic resonance, ultrasound) are expected to be capable of identifying tumors that are significantly smaller than those detected with current technologies.
- *Multifunctional nano-therapeutics and post-therapy monitoring tools.* Because of their multifunctional capabilities, nanoscale devices can contain both targeting agents and therapeutic payloads – features useful in drug delivery to areas of the body that are difficult to access because of a variety of biological barriers, including those developed by tumors. Thus, multifunctional nanoscale devices offer the opportunity to utilize new approaches to therapy – "smart" nanotherapeutics may provide clinicians with the ability to locally deliver the drug at lower doses, while maintaining high efficacy or time the release of an anticancer drug or deliver multiple drugs sequentially in a timed manner or at several locations in the body.
- *Devices and techniques for cancer prevention and control.* Nanotechnology can play a vital role in establishing novel approaches to the disease's prevention. For example, nanoscale devices may prove valuable in delivering or mimicking polyepitope cancer vaccines that engage the immune system or cancer-preventing nutraceuticals or other chemopreventive agents in a sustained, timed-release, and targeted manner. Nanotechnology can also enable techniques allowing for effective disease management and elimination of cancer spread to other organs.

The Alliance has generated very strong scientific output, which includes over 1,000 peer-reviewed publications in highly regarded scientific journals (an average impact factor ~7) and more than 200 patent disclosures/applications. In addition to scientific advances, the association of the program with nearly 50 industrial entities (ranging from PI-initiated start-up companies to collaborations with large multi-national firms) has established a vital commercial outlet for produced technologies. Currently, these companies along with the investigators from the ANC, are engaged in several nanotherapy and imaging clinical trials. Several additional companies have a nanotechnology application in advanced, pre-IND stage of technology development.

Due to the success of the ANC program, the National Cancer Institute approved reissuance. Phase II will start in September 2010 and will be funded for another 5 years. Phase II of the program will consists of Centers for Cancer Nanotechnology Excellence (CCNEs), Cancer Nanotechnology Platform Partnerships (CNPPs) and National Characterization Laboratory (NCL), similar to Phase I. In addition, Cancer Nanotechnology Training Centers (CNTCs) and Path to Independence awards will be also included to strengthen training and education facet of the program.

### 8.10.2 NHLBI Programs of Excellence in Nanotechnology (http://www.nhlbi-pen.net/)

*Contact person*: Denis Buxton, NIH/National Heart, Lung, and Blood Institute

The goal of National Heart, Lung, and Blood Institute (NHLBI) Programs of Excellence in Nanotechnology is to develop nanotechnology-based tools for the diagnosis and treatment of heart, lung, and blood diseases, and to move the translation of these technologies towards clinical application. Initially funded in 2004 with awards to four centers, the program brings together multidisciplinary teams from the biological, physical and clinical sciences for the focused development and testing of nanoscale devices or devices with nanoscale components, and applies them to cardiovascular, hematopoietic and pulmonary diseases. The program also develops investigators with the interdisciplinary skills to apply nanotechnology to heart, lung, and blood disease problems. The program is related to NHLBI's Strategic Plan Goal II: To improve understanding of the clinical mechanisms of disease and thereby enable better prevention, diagnosis, and treatment. Program highlights are available in a series of newsletters (http://www.nhlbi-pen.net/default.php?pag=news).

### 8.10.3 NIH Nanomedicine Common Fund Initiative (http://nihroadmap.nih.gov/nanomedicine)

*Contact person*: Richard Fisher, NIH/National Eye Institute

The Nanomedicine Initiative is a 10-year program that started in Fiscal Year 2005 as part of the NIH Roadmap for Medical Research. Currently, it operates under the auspices of the Common Fund which was established by Congress in the 2006 NIH Reauthorization Act as a central funding authority to support programs that are novel, unique, experimental, and relevant across all components of the NIH. The overarching goal of the Nanomedicine Initiative is to move basic science studies toward translational endpoints. In particular, the NIH Nanomedicine Initiative initially funded eight centers that were challenged to use quantitative approaches to understand, from an engineering perspective, the design of biomolecular structural and functional pathways in cells, and to use that information to design and build functional biocompatible molecular tools to return the dysfunctional structures or systems back into "normal" operating ranges after function has been perturbed by disease. The multidisciplinary teams carrying out this initiative consist of researchers with deep knowledge of biology and physiology, physics, chemistry, math and computation, engineering, and clinical medicine. During the first few years, the work emphasized basic biological studies, while keeping in mind that the choice and design of experimental approaches are directed by the need to solve clinical problems. More recently the focus has moved toward application of the basic biological information to specific clinical problems. Work at the centers has been evolving on a trajectory toward preclinical models that test new solutions to specific diseases. The program involves over 300 investigators including dozens of post-doctoral research associates and graduate students at over 30 educational institutions located in 12 states, and internationally in five countries.

## *8.11 Dragonfly TV: Nanosphere (http://pbskids.org/dragonflytv/nano)*

*Contact person*: Lisa Regalla, Twin Cities Public Television, Inc

*DragonflyTV* is an Emmy Award–winning children's multimedia science education program combining television, community outreach, print materials and science kits, and web-based information and activities. It is produced by Twin Cities Public Television in St. Paul, MN, and funded by the National Science Foundation. In its seventh season (2008), *DragonflyTV* teamed up with museums and research institutions nationwide to produce six, half-hour episodes on nanoscale science and engineering. The episodes are geared towards children ages 8–12 and follow a scope and sequence covering topics such as: size and scale, the structure of matter, size-dependent properties, nanoscale forces, applications, and societal implications.

Each episode includes two inquiry-based investigations, driven by kids, which reinforce the featured science concepts. In addition, each show contains a "Scientist Profile" that introduces role models and future careers in nanoscale science and engineering, and a segment called "Hey…Wait a Nanosecond," featuring real kids' opinions on societal implications.

Beyond broadcast, *DragonflyTV Nanosphere* resources include online videos, games, and activities; Educator Guides featuring inquiry-based activities for formal or informal use; a kids' nano "zine;" and the NanoBlast board game. These materials are distributed freely to educators through the National Science Teachers Association (NSTA), Association of Science Technology Centers (ASTC), and at NanoDays museum outreach events across the country.

## *8.12 Instrumentation for Education: NanoProfessor and NanoEducator (http://www.nanoprofessor.net/; http://www.ntmdt.com/platform/nanoeducator)*

*Contact person*: James Murday, University of Southern California Office of Research Adv ancement

Two public-private partnerships, NanoInk and NT-MTD, are seeking to make twenty-first-Century education and workforce development in nanotechnology accessible to small 2- and 4-year colleges, by providing relatively low-cost instruments and curricula.

The NanoProfessor project has three components. The first is an accessible desktop nanofabrication machine (Fig. 10) simple enough for general students to operate at the nanoscale level. The second critical element is a worthwhile curriculum grounded in fundamental science and engineering concepts; it is an interdisciplinary curriculum designed to engage students in basic science learning through hands-on manufacturing and experiments with cutting-edge technology at the nanoscale level. The curriculum is being developed by a team of teachers, NanoInk professionals, and experts in instructional design.

Each unit and the overall course will be evaluated during development and throughout implementation. The third element is the active participation of educational institutions committed to the advancement of science, technology, engineering, and mathematics education. The educational partners will host the project, receive training for faculty members, and cooperate in the evaluation and dissemination of project outcomes.

The NanoEducator platform is a student-oriented scanning probe microscope (SPM) that was developed for use by even first-time microscope users; it can navigate through step-by-step operations. This device is designed to capture student interest in science at secondary and post-secondary-levels and to train future nanotechnologists in using both atomic force microscopy (AFM) and scanning tunneling microscopy (STM) techniques. Robust and foolproof, NanoEducator can help provide a broad, interdisciplinary understanding of different fields of nanoscience, allowing investigation of cells, viruses, bacteria, metals, semiconductors, dielectrics, polymers, etc. It is designed it to be cost-effective enough to equip a classroom with SPMs and comes complete with e-teach software, training literature, handbooks, and descriptive laboratory exercises.

**Fig. 10** NanoInk desktop nanofabrication system

## *8.13 Three Illustrations of Newly Developed Innovative Nanoscale Instrumentation*

*Contact person*: James Murday, University of Southern California Office of Research Advancement

The development of scanning tunneling microscopy/spectroscopy and the various forms of atomic force microscopy in the 1980s led to the rapid explosion of science and engineering at the nanoscale. But to meet the growing complexity and sophistication of nano-enabled technologies, additional developments are needed for better (i.e., faster, more precise, 3D, etc.) measurement. There have been many contributions during the first decade of the nano-initiatives. Three examples that have reached the commercialization stage are CT (computed tomography) imaging, scanning helium ion microscopy, and imprint lithography.

The nanoXCT-100 is a lab-based ultra-high-resolution CT scanner for 3D visualization of microscopic sample volumes [38]. Precision X-ray focusing optics deliver a resolution as fine as 50 nm, seamlessly extending the capabilities of X-ray CT beyond those of conventional scanners. Integrated Zernike phase contrast imaging enhances the visibility of all edges and interfaces when absorption contrast is low. The nanoXCT-100 delivers reliable 3D volumetric information otherwise only accessible by cross-sectioning or other destructive methods. Dr. Ge Wang and his colleagues have been awarded more than $1.3 million from the National Science Foundation to develop the next-generation nano-CT imaging system, which promises to greatly reduce the required dose of radiation. Virginia Tech and Xradia, a leading nano-CT company, are also collaborating on the project with a cost-sharing investment of close to $800,000.

The scanning helium ion microscope (SHIM or HeIM) is a new imaging technology based on a scanning helium ion beam [39]. This technology has several advantages over the traditional scanning electron microscope (SEM). Due to the very high source brightness and the short De Broglie wavelength of the helium ions, which is inversely proportional to their momentum, it is possible to obtain qualitative data not achievable with conventional microscopes, which use photons or electrons as the light-emitting source. Images offer topographic, material, crystallographic, and electrical properties of the sample. In contrast to other ion beams, there is no discernible sample damage, due to the relatively light mass of the helium ion. A surface resolution of 0.24 nm has been demonstrated.

Nanoimprint lithography (NIL) is a method of fabricating nanometer-scale patterns [40]. It is a simple nanolithography process with low cost, high throughput and high resolution. It creates patterns by mechanical deformation of imprint resist and subsequent processes. The process has been commercialized by at least three companies: Nanonex (http://www.nanonex.com), NIL Technology (http://www.nilt.com), and Molecular Imprints (http://www.molecularimprints.com). NIL has been incorporated into the 32 and 22 nm nodes of the International Technology Roadmap for Semiconductors.

# 9 International Perspectives from Site Visits Abroad

## *9.1 United States-European Union Workshop (Hamburg, Germany)*

*Panel members/discussants*

Costas Charitidis (co-chair), Technical University of Athens, Greece
James Murday(co-chair), University of Southern California, United States
Nira Shimoni-Eyal, Hebrew University of Jerusalem, Israel
Helmuth Dosch, DESY, Germany
Massimo Altarelli, European XFEL GmbH, Germany
Dan Dascalu, University Politechnica Bucharest, Romania
Yvan Bruynseraede, Katholieke Universiteit Leuven, Belgium

Elaborating on European-wide attention to nanoscale science/engineering (e.g., see the European Nanotechnology Gateway: http://www.nanoforum.org, [41, 42]), there was an extensive European-wide study of the needs and opportunities for coordinating future research and development in nanomaterials science and nanotechnology for the advancement of technologies ranging from communication and information, health and medicine, future energy, environment and climate change to transport and cultural heritage. The result was the Gennesys report [43] that included challenges/opportunities for facilities and education. It provided the basis for this workshop report.

### 9.1.1 Facilities

The absence of central facilities for full parameter characterization of nanoparticles/materials is a bottleneck to advances in this critically important field; it is strongly encouraged a European Center of Excellence in nano-standardization and nanometrology be created. This would provide a scientific and industrial infrastructure in Europe for dimensional nanometrology and nanostandards specification (nanochemical, nanomechanical, nanobioproperties, nanoelectronics, etc.), reference materials, and standard measuring methods.

There are great advantages of nanomaterials, but they need to be carefully analyzed to identify any toxicology and environmental problems. Since the interactions of nanostructured materials with biological systems will be complex and levels of characterization different from the norm, a special center such as the U.S. National Institutes of Health Nanotechnology Characterization Laboratory should be established.

The strategic knowledge-based development of new nanomaterials, which are needed to solve urgent problems of society, requires creation of analytical science centers that cooperate in new ways with European research and have direct contact with neutron and accelerator-based x-ray facilities. These centers would address organizational aspects (availability, ease of access), educational aspects, and technical aspects (e.g., extreme focusing, nanobeam stations, small neutron beams, and transferring scientific results from laboratory conditions to realistic industrial ones).

On the one hand there is the European nanotechnology industry that needs to benefit from the best scientific data on materials it develops, on the other hand large facilities can provide such data but are not yet adapted to the industrial use. Hence the need to create an interface structure, EU-industry centers of excellence, whose mission is to bridge the gap between nanotechnology companies and large scientific facilities. This effort will seek to develop “pocket” facilities in order to democratize their use by making it accessible when it cannot be practiced on site, for example, control activities of production or treatment in hospital. Each EU-Industry Center of Excellence, would be focused around an urgent topic; the GENNESYS document proposes Softmatter Materials, Food, Science, Structural Nanomaterials, Nano-materials for Energy, and Nanomaterials for Cultural Heritage.

### 9.1.2 Education

A European action plan in nanomaterials education has to be worked out urgently to underpin a sustainable nanomaterials research strategy. Strong efforts must be undertaken to improve integration of nanomaterials education and research, particularly at the boundaries of disciplines and to prepare flexible and adaptable nanomaterials scientists and engineers for the future. An International Institute for Nanomaterials Education should be coordinated by the EC and/or other relevant agencies.

A new framework of cooperation between universities, national research institutes and industry needs to be developed. A Nanomaterials European College would ideally meet the requirements for the training of future materials scientists and engineers. It would be a central institute with satellite schools at the "Centers of Excellence" – and with close associations to recognized research universities and corporate research in industry throughout Europe. The International Institute for Nanomaterials would ideally complement the EIT (European Institute for Innovation and Technology). Joining both institutions would become the motor for "Innovative Europe" in nanomaterials science and technology.

In order to face up to the massive investments of major or emerging countries targeting world leadership in some economic areas, Europe and partner institutions must overcome the fragmentation of the human and materials resources of European research. This can be done by gathering the best teams to share these resources through integrating them into new European organizations such as the proposed GENNESYS European College of Excellence. The GENNESYS initiative represents a unique and attractive opportunity to gather and integrate geographically dispersed human resources and effectively scientific facilities for training and promoting activities.

Many companies throughout Europe and the world report problems in recruiting the types of graduates they need. For Europe to continue to compete alongside prestigious international institutions and programs on nanomaterials, it is important to create a "Europe Elite College" that provides a top-level education and the relevant skills mix. This should be a new institution, involving new "satellites" of leading universities and other institutions throughout Europe. Such a college should cover education, training, sciences and technologies for research, and have strong involvement by European industry. The elements for such a high level education are: multidisciplinary skills; top expertise in nanomaterials science and engineering; literacy in complementary fields; exposure to advanced research projects; literacy in key technological aspects; exposure to real technological problems; basic knowledge in social sciences, management, ethics, foreign languages; literacy in neighboring disciplines (international business, law, etc.); and interlinkages among education, research and industrial innovation. Students will be ready for that which research and development will provide. Sharing of post-docs, masters; and PhD students to foster the mobility of permanent researchers and professors between different institutions is needed to create "team spirit." The European College should have strong links with universities of excellence in Europe, nanomaterials research institutes, the research infrastructure, the centers of excellence, and industry.

Attention to the education/training of technicians is also necessary. Since experience with state-of-art fabrication/characterization/processing tools is essential, but difficult to sustain in a rapidly moving field such as nanoscale science and engineering, it will be necessary to work closely with the centers of excellence. Also needed is capability for remote access to that instrumentation.

Attention must also be devoted to primary and secondary education; in particular these education levels are important to stimulate interest in science/engineering careers. The EU has initiated the Know You project; during the 2009–2010 academic year 25 pilot schools have been teaching nanotechnology in their classrooms with a wide range of materials, including videos, online animations, games, workshops, virtual dialogues, and virtual experiments based on current research. Efforts such as this should be expanded and linked to international education efforts.

Consideration must be given to the research and development of an overall mechanism for efficient search, access, and use of cyber-infrastructure resources focused on nanoscience and technology with potential relevance to education at all levels. In particular, Wikipedia is becoming the *de facto* global encyclopedia; current Wikipedia entries addressing nanoscale science and engineering are woefully inadequate and must be updated, expanded, vetted, and sustained.

## *9.2 United States-Japan-Korea-Taiwan Workshop (Tokyo/Tsukuba, Japan)*

*Panel members/discussants*

Hiroyuki Akinaga (co-chair), AIST, Japan
Mark Hersam (co-chair), Northwestern University, United States
Ryoji Doi, Ministry of Economy, Trade and Industry, Japan
Isao Inoue, University of Tsukuba, Japan
Chul-Gi Ko, Korea Institute of Materials Science, Korea
F. S. Shieu, National Chung Hsing University, Taiwan
Masahiro Takemura, National Institute for Materials Science, Japan
Taku Hon-iden, Tsukuba City, Japan
Iwao Ohdomari, Japan Science and Technology Agency, Japan

### 9.2.1 Facilities

In addition to the points made in the workshop held in Chicago [44], the need for international collaborations was emphasized. As nanoscale science matures into technology innovations, those collaborations will have to address export-import controls. There is need for joint research contract templates to minimize that difficulty. Further, while semiconductor technologies presently lead R&D, this is beginning to change rapidly. The user facility infrastructures are not keeping pace with

| YEAR | STAGE OF EVOLUTION |
|---|---|
| ~2000 | Research by individual groups |
| ~2005 | User facility and network of user facilities |
| ~2010 | Problem-solving user facilities, and networking |
| ~2015 | User facility as a center of S&T formation |
| ~2020 | User facility in a society, as demonstrative test area and for outreach activities |

**Fig. 11** Evolution of user facilities from science and technology (S&T) to societal centers (From information provided by H. Akinaga)

**Fig. 12** Taiwan vision for nano-education (Courtesy of Prof. Fuh-Sheng Shieu, National Chung Hsing University, Taiwan)

the new needs. Finally, with the expected huge impact of nano-enabled technology toward the solution of societal needs, the user facilities need to evolve toward technology demonstration and public outreach activities (see Fig. 11).

### 9.2.2 Education

There was general agreement with the vision (see Fig. 12) presented by Prof. Fuh-Sheng Shieu, National Chung Hsing University, Taiwan. Taiwan, which has one of the more complete programs addressing education at the nanoscale [45], has begun a Phase II framework program that includes nanoeducation fundamental research, development of materials and curricula for elementary school through college, and popular science education.

There are education challenges and needs that must be addressed, including: multi-level collaboration amongst Universities, R&D Institutes, and Industry; communication with politicians, especially the next generation of policy makers – a challenge that suggests the incorporation of nanotechnology issues in business, law and medical education; reaching out to local governments which generally control K–12 education; and developing outreach materials that utilize nanotechnology as a new topic to interest students. For the latter there may be copyright issues associated with those materials impeding the rate of progress.

## *9.3 United States-Australia-China-India-Saudi Arabia-Singapore Workshop (Singapore)*

*Panel members/discussants*

Hans Griesser (co-chair), University of South Australia
Mark Hersam (co-chair), Northwestern University, United States
Chennupati Jagadish, Australian National University, Australia
Chen Wang, National Center for Nanoscience and Technology, China
Wei Huang, Nanjing University of Posts and Telecommunications, China
Jayesh Bellare, Indian Institute of Technology, Bombay, India,
Salman Alrokayan, King Abdullah Institute for Nanotechnology, Saudi Arabia
Andrew Wee, National University of Singapore, Singapore
Jackie Ying, Institute of Bioengineering and Nanotechnology, Singapore
Freddy Boey, Nanyang Technological University, Singapore

### 9.3.1 Facilities

The capital equipment awards made to facilities must include explicit funding for ongoing operational costs (e.g., staffing/technicians, maintenance). Further there is need to attract, train and retain technicians and PhD-level staff to make the best use of the facility equipment. To continue the rapid progress in nanoscale science/engineering/technology it is necessary to invest in new nanofabrication, characterization, and computational tools and infrastructure, not only for research but also for educational needs. There must also be attention to standardized nanosafety protocols and guidelines.

### 9.3.2 Education

For K–12, the nanoscale can provide illustrations of multidisciplinary approaches toward the solution of social needs, a useful approach to avoid over specialization in students at their formative stage. Authenticated, peer-reviewed education aids should be made available, including the use of social media tools. University undergraduate and graduate students should be encouraged to visit K–12 classes.

At the University level, for students to be proficient at the nanoscale they need a working knowledge in physics, chemistry, engineering and biology – a challenge in our discipline centric education systems. At the undergraduate level, elective courses (including laboratories) are recommended, but they should have high scientific rigor (superficial courses would not be recommended). A web-based portal for authenticated, peer-reviewed teaching materials would have high value. Both joint nanoscience-journalism/communication programs and continuing education may help coping with the dwindling number of science journalists and teachers.

To better inform the public it will be necessary to be proactive in popular media, i.e. do not simply react to negative events. Nongovernmental organizations and activist groups need to be engaged in the dialog on nanosafety, and this may require different approaches in different countries based on local cultural mores. Informal science education (e.g., museums, mobile displays) is an important means for disseminating the successes of nanoscience to the general public.

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