Integrating Nanoscience into the Classroom: Perspectives on Nanoscience Education Projects

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ABSTRACT The National Nanotechnology Initiative has motivated substantial growth in nanoscience and nanotechnology research in the United States and beyond. One of the central goals of the National Nanotechnology Initiative is the development and education of future generations of nanoscience researchers. This Nano Focus provides a brief history of nanoscience education, including curricula that have been implemented successfully into secondary and college institutions, as described in the symposium "Integrating Nanoscience into the College and High School Classroom" at the 237th American Chemical Society National Meeting in March 2009.

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10.1021/nn900335r CCC: $40.75

Nanoscience education is still in its infancy, and unlike other areas of science education, the understanding and research on how to teach the core ideas of nanoscience and nanotechnology are still emerging. The area of nanoscience and nanotechnology education took on greater importance with the inception of the National Nanotechnology Initiative (NNI) in 2001. With the NNI came the commitment from the United States to be a world leader in nanoscale science and engineering research. To meet this goal, it will be imperative to develop a strong pipeline of nanoscale researchers. One of the central missions of the NNI is to "develop and sustain educational resources, a skilled workforce, and the supporting infrastructure and tools to advance nanotechnology".[1] The NNI provides considerable funding to support the development of nanoscience education materials as well as research into how students best learn nanoscience concepts. We are now building the knowledge base to propel nanoscience education forward. In this Nano Focus, a brief history of the growth of nanoscience education will be presented, as well as highlights of several nanoscience education projects as presented at the "Integrating Nanoscience into the College and High School Classroom" symposium at the 237th American Chemical Society National Meeting held March 2009.[2]

> One of the central missions of the National Nanotechnology Initiative is to "develop and sustain educational resources, a skilled workforce, and the supporting infrastructure and tools to advance nanotechnology".

The Need for Nanoscience Education. According to Mihail C. Roco, the senior advisor for Nanotechnology at the National Science Foundation (NSF), "a key challenge for nanotechnology is the education and training of a new generation of skilled workers".[3] He estimates that by 2015 there will be a need for a workforce of approximately 2 million scientists and researchers in nanoscience.[3] To meet these needs and prepare the next generation of leaders in nanotechnology, education must be a priority. To address the issues of education, a sizable portion of the NNI budget has gone to support programs that promote nanoscience education. The 2009 NNI budget provides funding of $40.7 million toward nanoscience education, most of which is available through education programs supported by the NSF (Figure 1).[4] These funds support a variety of nanoscience projects ranging from the Nanoscale Informal Science Education Network (NISE Net), a network of science museums with the common goal of promoting informal nanoscience education projects,

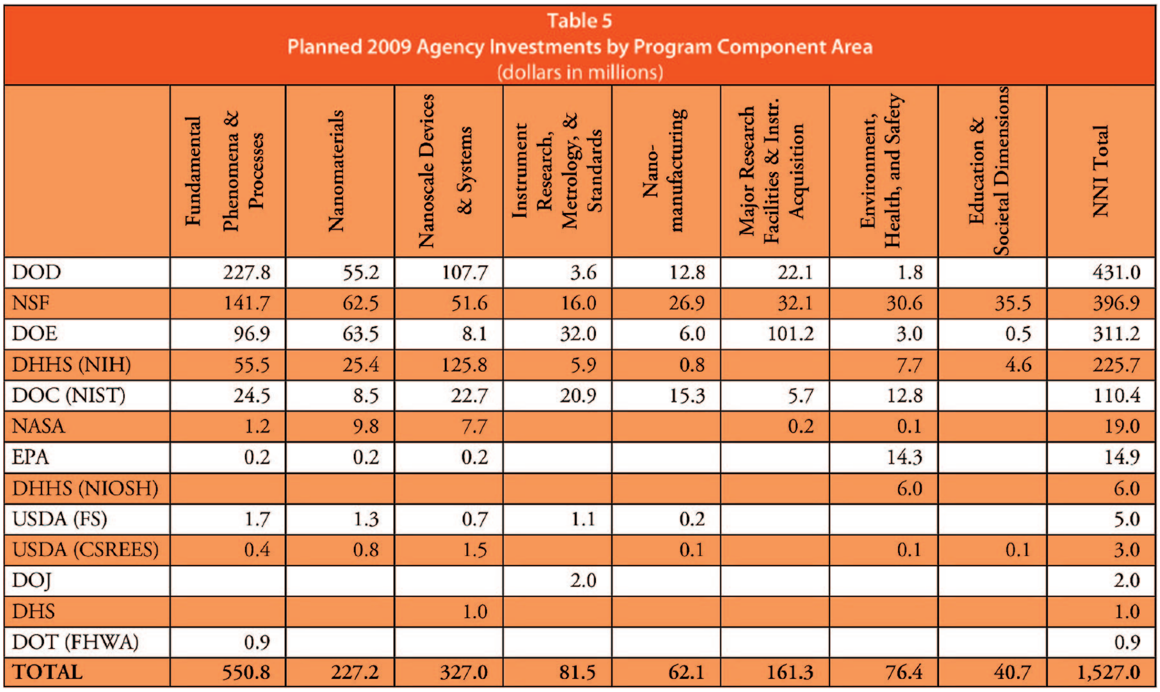


Table 5
Planned 2009 Agency Investments by Program Component Area
(dollars in millions)

	Fundamental Phenomena & Processes	Nanomaterials	Nanoscale Devices & Systems	Instrument Research, Metrology, & Standards	Nano-manufacturing	Major Research Facilities & Instr. Acquisition	Environment, Health, and Safety	Education & Societal Dimensions	NNI Total
DOD	227.8	55.2	107.7	3.6	12.8	22.1	1.8		431.0
NSF	141.7	62.5	51.6	16.0	26.9	32.1	30.6	35.5	396.9
DOE	96.9	63.5	8.1	32.0	6.0	101.2	3.0	0.5	311.2
DHHS (NIH)	55.5	25.4	125.8	5.9	0.8		7.7	4.6	225.7
DOC (NIST)	24.5	8.5	22.7	20.9	15.3	5.7	12.8		110.4
NASA	1.2	9.8	7.7			0.2	0.1		19.0
EPA	0.2	0.2	0.2				14.3		14.9
DHHS (NIOSH)							6.0		6.0
USDA (FS)	1.7	1.3	0.7	1.1	0.2				5.0
USDA (CSREES)	0.4	0.8	1.5		0.1		0.1	0.1	3.0
DOJ				2.0					2.0
DHS			1.0						1.0
DOT (FHWA)	0.9								0.9
TOTAL	550.8	227.2	327.0	81.5	62.1	161.3	76.4	40.7	1,527.0

Figure 1. The 2009 NNI budget listed by program category and funding agency. Reproduced from ref 4. Public domain work for domestic uses in the U.S.

tothe National Center for Learning and Teaching in Nanoscale Science and Engineering, a national center to support all aspects of learning and teaching of nanoscience and engineering.

National Center for Learning and Teaching in Nanoscale Science and Engineering. Since the late 1990s there has been considerable growth in interest in nanoscience education by education and science researchers. The first article in the *Journal of Chemical Education* that includes nanotechnology as a topic appeared in 1995.[5] For the seven-year period from 1995 to 2001 there were a total of 28 articles published in *Journal of Chemical Education* with a topic of nanotechnology; over roughly the next seven years there were 94 nanotechnology articles published in the same journal, an increase greater than 3-fold. To help the discipline move forward, the NSF established The National Center for Learning and Teaching in Nanoscale Science and Engineering (NCLT) in 2004 under the direction of Professor Robert Chang of Northwestern University. The multi-institution NCLT is divided into five core areas: [6]

1. Learning Research,
2. Nano Concept, Course, and Learning Technology Development,
3. Professional Development,
4. Resource Dissemination, Networking and Community Building, and
5. Evaluation and Assessment.

Big Ideas in Nanoscale Science: Grades 7-12

1. Size and Scale
2. Properties of Matter
3. Particulate Nature of Matter
4. Modeling
5. Dominant Forces
6. Tools
7. Self-Assembly
8. Technology and Society

Figure 2. The "Big Ideas" in nanoscience for grades 7−12 based on the National Center for Learning and Teaching in Nanoscale Science and Engineering.[7]

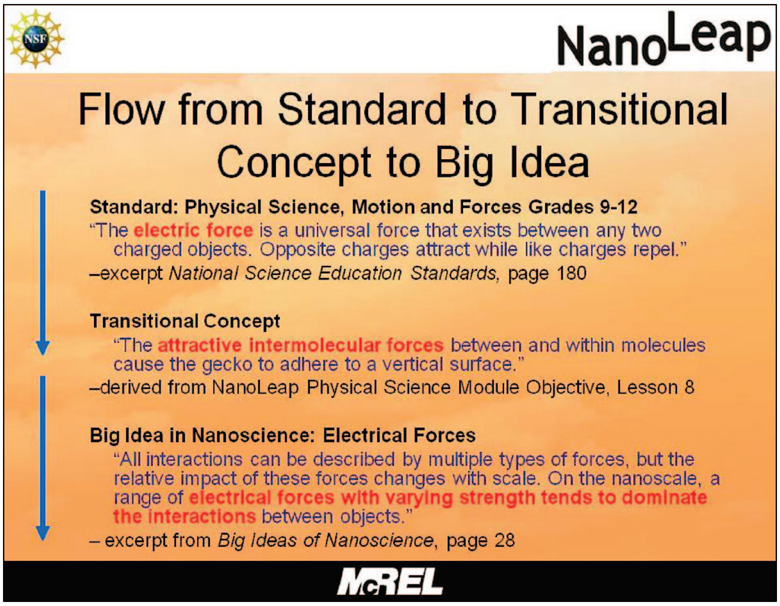
The work of the NCLT has been instrumental in helping to build and guide a community of nanoscience educators, particularly at the 7th−16th grade range. Through annual workshops, weekly web seminars, and teacher professional development programs, the NCLT has helped to define learning goals for nanoscience education (Figures 2 and 3).[7] These goals serve as a framework for development of nanoscience education lessons at the secondary and college education levels.

Integrating Nanoscience into the High School Classroom. The idea of integrating what is perceived by many secondary educators to be a new science into the secondary school classroom is a difficult task. Where do educators and curriculum developers begin? From a teaching and curriculum perspective, should nanoscience be considered a new discipline, or can it be spread throughout the secondary science education curriculum based on its interdisciplinary nature? As nanoscience researchers, we understand nanoscience as an interdisciplinary field that is at the interface of different scientific and engineering dis-

Big Ideas in Nanoscale Science: Grades 13-16

1. Size and Scale
2. Size Dependent Properties
3. Tools & Instrumentation/ Characterization
4. Models & Simulations
5. Surface-Dominated Behavior
6. Societal Impact/Public Education
7. Self-Assembly
8. Surface-to-Volume Ratio
9. Quantum Mechanics

Figure 3. The Big Ideas in nanoscience for grades 13−16 based on the National Center for Learning and Teaching in Nanoscale Science and Engineering.[7]



NanoLeap

Flow from Standard to Transitional Concept to Big Idea

Standard: Physical Science, Motion and Forces Grades 9-12
"The **electric force** is a universal force that exists between any two charged objects. Opposite charges attract while like charges repel."
–excerpt *National Science Education Standards*, page 180

Transitional Concept
"The **attractive intermolecular forces** between and within molecules cause the gecko to adhere to a vertical surface."
–derived from NanoLeap Physical Science Module Objective, Lesson 8

Big Idea in Nanoscience: Electrical Forces
"All interactions can be described by multiple types of forces, but the relative impact of these forces changes with scale. On the nanoscale, a range of **electrical forces with varying strength tends to dominate the interactions** between objects."
– excerpt from *Big Ideas of Nanoscience*, page 28

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Figure 4. Example of how the concept of intermolecular forces as used in the NanoLeap unit of Physical Science can be used to connect standard core concepts to one of the Big Ideas in Nanoscience. Reproduced with permission from ref 10. Copyright 2008, Midcontinent Research for Education and Learning.

ciplines. We can build on these connections to make interesting and groundbreaking discoveries. Yet, for a high school teacher, these connections are not always as apparent and require well-designed curricula and professional development to help bridge the connections and make integration into their classrooms a less daunting task.

A number of nanoscience education projects are designed to enable successful integration of nanoscience into the secondary classroom. A brief description and outcomes of some of the projects presented at the "Integrating Nanoscience into the College and High School Classroom" symposium at the 237th national meeting of the American Chemical Society in March 2009 are presented below.

> Should nanoscience be considered a new discipline, or can it be spread throughout the secondary science education curriculum based on its interdisciplinary nature?

In 2004, the NSF funded two large-scale 7th−12th grade curriculum development projects, NanoLeap[8] and NanoSense.[9] Each of these projects had the goal of developing, implementing, and evaluating nanoscale science and engineering content for the secondary school STEM curriculum. The NanoLeap project, under the direction of John Ristvey at the Mid-Continent Research for Education and Learning, had two goals related to the development of two 3-week comprehensive STEM lessons to replace existing classroom lessons.[8]

- To explore where nanoscale science, technology, engineering, and mathematics concepts can fit into high school physical science and chemistry classes in a manner that supports students in learning core science concepts.
- To determine a viable approach for instructional materials development in the areas of nanoscale science, technology, engineering, and mathematics.

The NanoLeap team's approach to development was to design their lessons to meet four desired student outcomes.

1. *Outcome no. 1:* support inquiry-based teaching and learning.
2. *Outcome no. 2:* increase levels of interest and engagement in learning science.
3. *Outcome no. 3:* increase understanding of core science concepts.
4. *Outcome no. 4:* increase understanding of nanoscale science, technology, engineering, and mathematics concepts, applications, and careers.

During the development process the NanoLeap team worked with 16 middle and high school teachers who assisted with content development and pilot testing of the two units. The project deliverables included units on physical science and chemistry.

1. *Exploring the Mystery of the Gecko—Physical Science* "What factors affect force measurements between interacting surfaces?"
2. *Nanoscale Materials and their Properties—Chemistry* "How and why do the chemical and physical properties of nanosamples differ from those of macrosamples of the same substance?"

The NanoLeap curriculum units were designed to include transitional concepts that connect core science concepts as found in the National Science Education Standards and those as defined in the Big Ideas in Nanoscience (Figures 4 and 5). Evaluation of the NanoLeap project found that the curriculum that was developed was successful with meeting outcomes 1, 3, and 4 with large increases in outcomes 3 and 4 and no statistically significant increase in outcome 2.[10]

The NanoSense project, under the direction of Patty Schank and Tina Stafford at SRI International, builds on the success of their ChemSense

Figure 5. Schematic showing how the NanoLeap curriculum bridges the gap between core learning concepts and Big Ideas in Nanoscience. Reproduced with permission from ref 10. Copyright 2009, Midcontinent Research for Education and Learning.

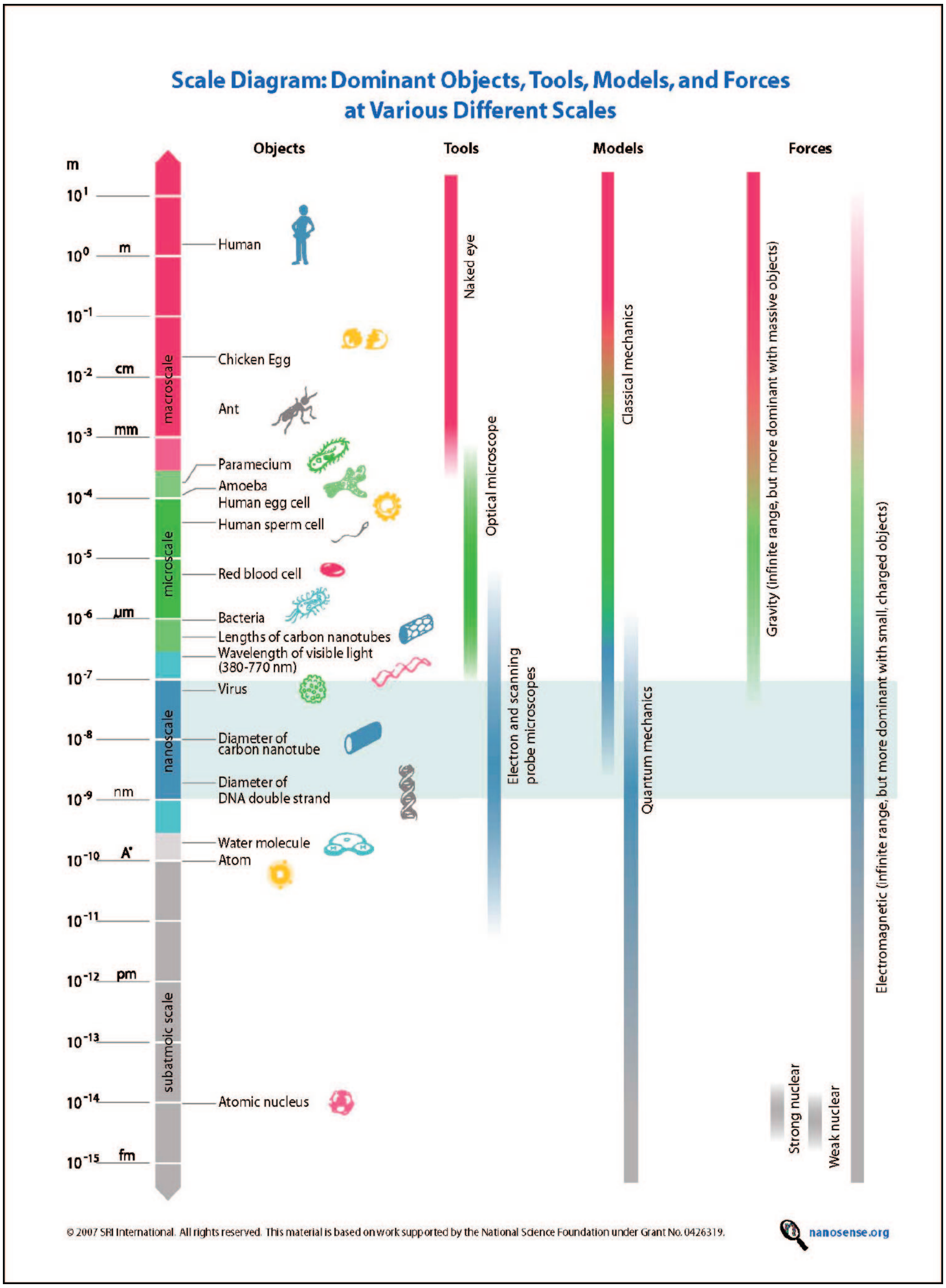

Figure 6. Size and Scale poster developed as part of the NanoSense project. The poster connects objects, tools, models, and forces to different length scales. Reproduced with permission from ref 12. Copyright 2007, SRI International.

project.[11] The SRI team developed four curriculum units for incorporation into the 7th−12th grade classroom.[9]

- Size Matters (size and scale)
- Clear Sunscreen (nanoparticles)
- Clean Energy (nanosolar cells)
- Fine Filters (nanofiltration)

Unlike the NanoLeap project, the units developed by the NanoSense team were designed “to integrate in an opportunistic manner with the regular curriculum”.[12] The constructivist lessons are centered around exciting applications to hook students.

Classroom evaluation of the NanoSense units showed that students were able to learn simple nanoscience and engineering concepts, such as naming properties that changed at the nanoscale (Figure 6), using correct vocabulary when describing the nanoscale, and providing superficial descriptions of nanotechnology applications. In general the students had a difficult time providing the underlying scientific principles that lead to properties at the nanoscale.[13] More general conclusions from the NanoSense evaluation included the difficulty teachers experienced in implementing enough nanoscale science and technology material to produce deep understanding of nanoscience concepts. For instance, it was not possible for students to learn nanoscience concepts without a firm

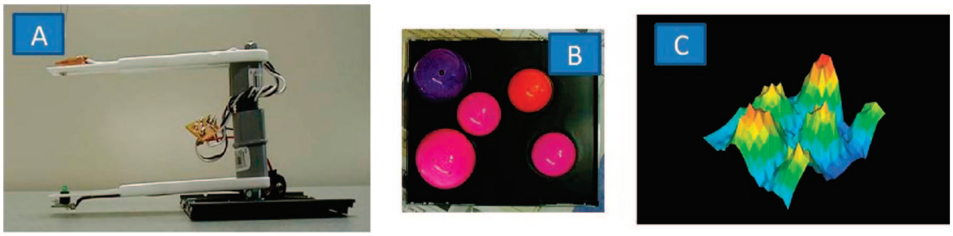

Figure 7. (A) Picture of an inexpensive working model of a scanning tunneling microscope (STM). The model was developed for the University of Wisconsin-Madison Nanoscale Science and Engineering Center by Maynard Morin. (B) A sample of a surface made of a CD case and plastic eggs that is analyzed with the model STM. (C) The output of the analysis of surface in from the model STM. Photos courtesy of The Nanoscale Science and Engineering Center at the University of Wisconsin-Madison.

understanding of the model of the atom, fundamental particles, and small clusters of ionic compounds, and finally students did not understand the dominant forces at different size scales.[13]

Professional Development for 7th—12th Grade Teachers. To integrate any new curriculum into a middle and secondary school classroom effectively, it must be embraced by the science teachers at those grade levels. Teachers must feel confident in their understanding of the content areas that they are to teach to their students. Nanoscience provides a challenge for teachers as many of them have not encountered nanoscience concepts in their science coursework. Effective teacher professional development programs for inclusion of nanoscience into the curriculum are paramount. A number of current projects focus on developing and evaluating innovative nanoscience professional development programs for teachers, several of which are outlined below.

One of the core areas of the NCLT is professional teacher development programs for teachers. The NCLT has five major goals of their professional development activities:[14]

> Effective teacher professional development programs for inclusion of nanoscience into the curriculum are paramount.

- provide secondary science teachers with enhanced content knowledge of nanoscale science and engineering (NSE) concepts
- introduce teachers to inquiry-based methods for teaching NSE
- provide secondary teachers with NSE lessons applicable to their classrooms
- assist teachers in developing and integrating their own NSE lessons
- enhance teachers' awareness of the interdisciplinary nature of NSE

To help meet these goals the NCLT hosts annual intense two-week summer institutes for teachers. During their two-week experiences, teachers perform nanoscience lessons, attend seminars from nanoscience researchers, and participate in relevant nanoscience experiments. As a capstone to their two-week experiences, the teachers develop a nanoscience lesson for inclusion in their classrooms. During the following school year, participating teachers receive follow-up with NCLT professional developers in the form of classroom observations, focus groups with other participating teachers, and weekend interviews. An evaluation of the 2007 cohort of 12 teachers found that teachers were more likely to develop a lesson related to topics already taught in their classrooms. In the 2007 cohort 5 of the 12 lessons designed were on the topic of intermolecular forces. Several themes emerged from the evaluations of the 2007 cohort as to what limited the integration of nanoscience lessons into classrooms.[14] Teachers were less likely to implement a nanoscience lesson if they found the material to be of little relevance to course content or if the teacher did not feel she/he had a strong enough background in nanoscience content. In some cases, the curriculum their school district used was inflexible to addition of new material. Some teachers noted a lack of student interest in the topic and insufficient staff support for proper implementation of nanoscience lessons in their classrooms, all of which contributed to low levels of integration.

The Online Nanoscience Course for Teachers is a novel professorial development project originating at the University of Wisconsin-Madison and now continued at Central Michigan University. Designed by Janice Hall Tomasik as a graduate student with the University of Wisconsin-Madison Nanoscale Science and Engineering Center and Institute for Chemical Education, the innovative course was developed with the goal of building a virtual community of nanoscience educators.[15] Teachers from around the country participate in the eight-week distance-learning course, which includes weekly online chats between nanoscience researchers and educators about current nanoscience research topics. The teachers learn about topics ranging from "Properties of Nanomaterials" to "Societal Impacts of Nanotechnology". Throughout the course, teachers use the knowledge they gain to develop a new nanoscience lesson for use in their classroom. One of the highlighted lessons developed was a creative usable model of a scanning tunneling microscope (STM) developed by Massachusetts high school teacher Maynard Morin (Figure 7).

The Center for Biological and Environmental Nanotechnology (CBEN) at Rice University has developed and taught a graduate course for teachers that uses virtual laboratory tours as a means to teach current trends in nanoscience research.[16] The simple but effective videos feature CBEN graduate student and postdoctoral researchers discussing and demonstrating their research. Throughout the course, teachers use the videos to supplement more traditional classroom formats. At the end

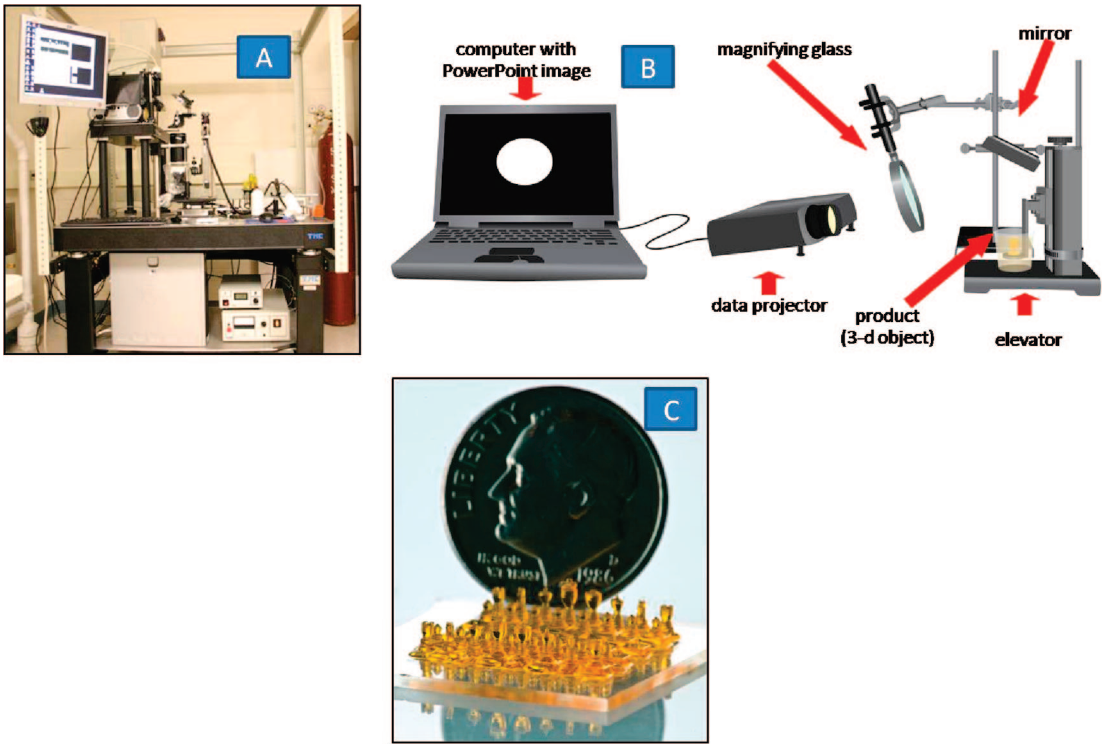

Figure 8. (A) Image of the setup developed by Nicholas Fang at University of Illinois, Urbana−Champaign for 3D printing using nanoscale optical imaging. (B) Cost effective model developed by Joseph Muskin for use in college and high school classrooms. (C) Samples of 3D objects that can be made using the apparatus shown in part B with a UV active polymer. Photo used in part A courtesy of Professor Nicholas Fang/University of Illinois, Urbana−Champaign. Graphic used in part B and photo used in part C courtesy of Joseph Muskin/University of Illinois, Urbana−Champaign.

of the course, each teacher develops a nanoscience lesson to take back to their classroom.

Integrating Nanoscience into the College Classroom. The nature of the college classroom makes for easier integration of nanoscience concepts than the secondary classroom. Undergraduate students have a greater scientific understanding compared to high school students, and, in most cases, college course instructors are better prepared to teach the underlying scientific concepts than their secondary school counterparts. The explosion of discoveries at the nanoscale has led to considerable impact on the undergraduate chemistry curriculum. A quick search of the recent chemical education literature finds papers on individual laboratory exercises that are integrated in chemistry courses[17] to whole courses on nanoscience.[18] Below are descriptions of some of the exciting nanoscience laboratories developed based on current nanoscience research and a course that utilizes the current nanoscience literature to teach students basic chemistry concepts.

Figure 9. (A) Students in Chemistry 150: Nanochemistry at Beloit College synthesizing nanoparticles. (B) Students in Chemistry 150: Nanochemistry at Beloit College preparing a presentation on a current nanoscience research topic. Photos courtesy of George Lisensky/Beloit College.

Research on three-dimensional (3D) printing at the nanoscale at the Center for Nanoscale Chemical−Electrical−Mechanical Manufacturing Systems at the University of Illinois-Urbana−Champaign (UIUC) has led to a novel inexpensive laboratory suitable for use in college and high school classrooms. The lesson, developed by Joseph Muskin, is based on the work of UIUC professor Nicholas Fang. Fang's research focuses on the development of a 3D printing process using nanoscale optical imaging with a photoactive polymer to make

3D structures.[19] The cost of his laboratory setup for the printing process is approximately $500,000 (Figure 8), far more than a typical undergraduate laboratory can afford. To mimic the process, Joseph Muskin developed a portable system that utilizes a computer projector, simple computer drawings, and an easy to build elevator system (Figure 8). Using a photosensitive monomer and a UV light absorber, Muskin and colleagues can produce intricate 3D structures and accurately model the process being developed in his research center (Figure 8).

Another example of modeling nanoscience research for integration into the undergraduate classroom comes from Professor Thomas Ticich at Centenary College in Louisiana. Ticich was seeking a safe and suitable method to synthesize carbon nanotubes in his undergraduate laboratory. The most common method from the chemical education literature for making carbon nanotubes required a tube furnace to be heated to 1000 °C.[20] Having recently read in the literature several methods for making carbon nanotubes in ethanol flames,[21,22] Ticich developed an undergraduate laboratory for the synthesis of carbon nanotubes using a simple ethanol burner.[23]

An excellent example of how to integrate an entire nanoscience course into the undergraduate chemistry curriculum effectively was presented by Professor George Lisensky of Beloit College.[24,25] Lisensky developed two nanoscience courses offered at Beloit College, a first-year seminar[26] that has evolved into a full chemistry course[27] designed for first-year undergraduates. Professor Lisensky effectively integrates current literature with numerous laboratory experiments into the course design. Students participating in the course prepare weekly literature reports from current papers published in nanoscience and nanotechnology journals (Figure 9). The papers are selected by students who present an overview of the research to their peers. To augment the current research literature and lecture in the course, students have a weekly laboratory assignment taken from the online video laboratory manual from the University of Wisconsin-Madison Materials Research Science and Engineering Center.[28] Sample laboratory exercises include "Preparation of Cadmium Selenide Quantum Dot Nanoparticles",[29] "Synthesis of Nickel Nanowires",[30] and "Synthesis of Gold Nanoparticles".[31]

FUTURE PROSPECTS

The future looks very bright for nanoscience education. As the field matures and we gain a better understanding of how students conceptualize the properties of nanoscale materials, educators and developers of nanoscience curricula will be better able to design educational materials that assist students in learning these concepts. Challenges still exist for the integration of nanoscience into both high school and college classrooms. One of the most important challenges we face is with integration into the secondary school classroom and proper professional development of our science teachers. Until we have a generation of science teachers who are exposed to nanoscience concepts during their college classes, we will need to rely on professional development opportunities to enable teachers to understand nanoscale concepts needed for proper implementation of nanoscience-focused educational materials. One of the challenges to integration into the college classroom is the need to keep the material current. With new discoveries advancing the field on a continual and rapid basis, there is the possibility that nanoscience educational materials used in the college classroom can quickly become out of date. It is important that college educators continue to develop new and exciting courses and laboratory exercises that capture the imagination of their students.

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