Nano2Earth: Incorporating Cutting-edge Research into Secondary Education Through Scientist-Educator Partnerships

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ABSTRACT

Agencies such as the National Science Foundation have identified as a priority the incorporation of cutting-edge research into secondary science curriculum. The Nano2Earth project, a component of an NSF-sponsored nanoscale science and technology research program, provides an example of how scientist-educator partnerships have been essential in the production of classroom materials designed for secondary school students that incorporate cutting-edge research. Nano2Earth uses groundwater quality as a framework for the introduction and application of nanoscience and nanotechnology through teacher resources and lesson plans. Scientist-educator partnerships were formed to bridge the knowledge and culture gap between research and secondary education, develop proxies for advanced technologies for classroom activities, and address national and state standards. The development of the Nano2Earth project is evaluated within the framework of criteria for successful scientist-educator partnerships drawn from the literature. The involvement of graduate students provides a means to accomplish project goals, in addition to preparing a future generation of scientists and educators who are more prepared to address the broader impacts of their disciplines.

INTRODUCTION

Perhaps more than ever, direct ties between current scientific research, both the content and methods, and the benefit of the general public and society are sought and encouraged by federal agencies. Recent trends in research funding priorities, such as the National Science Foundation's "broader impacts" criteria, have influenced grant seeking-researchers to address a variety of societal issues in their proposed projects by 1) advancing discovery and understanding while promoting teaching, training, and learning, 2) broadening participation of underrepresented groups, 3) enhancing infrastructure for research and education, 4) broadening dissemination to enhance scientific and technological understanding, and 5) benefiting society (NSF, 2004). Principal investigating scientists rarely have experience with outreach and educational programs, yet they are expected to successfully implement them. One strategy for successfully meeting the "broader impacts" criteria involves forming partnerships with science educators, teachers, museums, or other existing infrastructure elements that can provide the additional experiences perspectives, and knowledge needed. Developing and maintaining these partnerships may be time and energy intensive for all parties involved due to the conventional differences in the cultures of the scientists, the university educators, and the K-12 educators (Gomez et al., 1990; Carriuolo, 1996; Gosselin et al., 2003; Hall-Wallace and Regens, 2003). Additionally, cost may play a deciding factor in supporting everything from informal gatherings and travel expenditures to material resources.

The broader impacts criteria highlight the disconnect between cutting-edge scientific research and the material to which K-12 students are typically exposed. An

NSF-sponsored workshop report recommended strategies for including cutting-edge research data and tools into the classroom lessons, as well as developing curricula with stronger interdisciplinary connections (NSF, 1997). These strategies should be a major consideration as participants of scientist-educator partnerships construct the frameworks for their collaborative ventures of developing materials appropriate for secondary education courses. The purpose of this article is to describe how a scientist-educator partnership was essential for the realization of an outreach and educational component of a National Science Foundation research grant in nanoscale science. The partners were successful in designing a curriculum, Nano2Earth, that strengthened the connections between cutting-edge research and the K-12 classroom, while emphasizing the dual impact of nanoscience and nanotechnology on natural Earth processes.

To develop the Nano2Earth curriculum, we assembled a collaborative team of interdisciplinary scientists, researchers in science education, and experienced secondary science teachers who had content expertise in biology, chemistry, Earth science, and physics. The partners in the collaboration worked together over a period of four years learning about each others' work, laying the groundwork for the curriculum, and designing and field-testing the classroom activities. A number of essential and informative workshops involving all participants focused on nanotechnology research experiences led by researchers (faculty and graduate students) in nanoscale science, discussions of curriculum development models and national/regional science education standards led by science education researchers, and curriculum development sessions led by teachers. Assessment of the project was accomplished by a doctoral researcher from the Virginia Tech Department of Sociology through continued observation and interviews with team members.

Nanoscience and nanotechnology are cutting-edge scientific fields that cross all boundaries of biology, chemistry, engineering, and physics (Roco, 2004). Certainly not an exception, the Earth and environmental sciences have a rich developing research thrust in nanoscale science and technology (Banfield and Navrotsky, 2001; Hochella 2002a; Hochella, 2002b). "Nano" refers to a measure of scale equaling one billionth, or 10^{-9}. Examples of nano-units include a nanometer (10^{-9} m) and a nanoNewton (10^{-9} N). Nanoscience explores the changes in properties and reactivity of material as a function of the material size. Largely within the past two decades, scientists have begun studies that reveal how properties of materials typically vary over the length scales of 1-100 nm, above which the material properties are constant. Melting point, electrical conductivity, magnetic behavior, color, and mechanical strength are examples of properties that have been observed to change quite dramatically in the nano-range. Nanotechnology refers to the application of these property changes for some advantageous purpose. Additionally, nanotechnology allows measurements and experiments investigating phenomena that were not previously accessible. One such application is the measurement of forces between two small objects. These forces of interaction, collected over a separation distance of nanometers, provide quantitative information about the incredibly tiny forces (nanoNewtons) that often can be used to describe how the objects will stick when brought together. For example, the forces measured between a bacteria and mineral can be used to investigate the transport of bacteria through groundwater (Cail and Hochella, 2005) or how the bacteria might be using the mineral for anaerobic respiration (Lower et al., 2001).

It is estimated that potentially 12 million workers trained in nanoscience and nanotechnology will be required worldwide by the year 2015 (Roco, 2003a). The current opportunities for K-12 students to learn about nanoscience and nanotechnology are extremely limited (Roco, 2003a) despite the likelihood that these fields will have a massive impact on human society (Roco, 2003b). The Earth and environmental sciences provide an excellent setting for the development of new concepts, such as nanoscience, and transfer of those concepts between traditional scientific disciplines due to the emphasis on natural phenomena that are inherently and necessarily interdisciplinary. The Nano2Earth curriculum takes advantage of these natural connections by including chemistry concepts such as electron transfer, pH, and redox potential; concepts from biology such as aerobic/ anaerobic respiration, ecosystems, and eutrophication; and concepts from physics such as the behavior of springs.

This case study describes the roles of scientists and educators who were involved in a partnership to develop a secondary nanoscience and technology curriculum for Earth science, environmental science, biology, and chemistry teachers through investigations of groundwater. At a general level, the Nano2Earth project fits the 'best practices' outlined in a 2005 NSF-sponsored workshop report designed to aid effective implementation of broader impacts activities (Scotchmoor et al., 2005), including the recommendation that broader impacts not be handed over solely to outreach personnel, but rather there be an integrated team of which scientists play a part. In the light of outreach mandates by the NSF, it is important for scientists to understand the characteristics of a collaboration that promotes the partners' successful development of a curriculum that connects high school students to exciting current scientific research.

To our knowledge, the Nano2Earth project is the only existing comprehensive secondary-level curriculum designed to introduce nanotechnology and support its connections to content in other courses such as biology, chemistry, and Earth and environmental science. A majority of other nano-outreach projects to date have focused on research experiences for undergraduates and/or teachers (Batterson, 2002). Other outreach programs, although not comprehensive curricula, are directed to K-12 students. Three examples include individual K-12 modules that have been developed at the University of Wisconsin-Madison (Exploring the Nanoworld, http://mrsec.wisc.edu/Edetc/modules/), "It's a Nano World", a traveling museum exhibit developed by the Nanobiotechnology Center at Cornell University (http://www.itsananoworld.org/), and the nanoManipulator at the University of North Carolina - Chapel Hill which allows students to remotely control an atomic force microscope (AFM), one of the most important tools in nanotechnology (Jones et al., 2003).

1. Introduction to Nanotechnology
   Engage: Brainstorming Activity
   Explore: Scaling Activity
   Explain: What is nanotechnology? (reading assignment with questions)
   Elaborate: Current Events in Nanotechnology Webquest
   Evaluate: Presentation of Current Events
2. Introduction to Water Pollution
   Engage: Teacher Demonstration: What is in this glass of water?
   Explore: Water Testing Activity
   Explain: Water Pollution KWL Chart
   Elaborate: Water Pollution Webquest
   Evaluate: Completion of KWL Chart and Writing Activity
3. Microbe-Mineral Interactions
   Engage: Prelab Questions
   Explore: Winogradsky Column Lab Activity
   Explain: Discussion and Sharing of Results
   Elaborate: Groundwater Scenario
   Evaluate: Analysis and Conclusion Questions
4. Bacterial Transport in Groundwater
   Engage: Groundwater Scenario
   Explore: Bacterial Transport in Sand Column Lab
   Explain: Class Discussion and Questions: Bacteria Transport Lab
   Elaborate: Influence of Groundwater Chemistry on Bacterial Transport Lab
   Evaluate: Webquest Activity on Bacteria and Groundwater Pollution
5. The Atomic Force Microscope: Nanoforces in Nature
   Engage: Questions: What have we learned about microbe-mineral interactions and bacterial transport?
   Background reading: Atomic Force Microscope
   Explore: Activity: What happens when we bring bacteria and minerals together?
   Explain: Computer Simulation of Force Curve
   Elaborate: Interpreting Force Curve Data
   Building Model AFM (optional)

Table 1. Contents of Nano2Earth lessons. Each lesson contains a 5-E cycle.

CURRICULUM DESCRIPTION AND SELECTED EXAMPLES

The Nano2Earth curriculum consists of 5 lessons (Table 1), all of which make substantial interdisciplinary links across subject areas represented in the project. These lessons were intentionally designed to be flexible, providing several opportunities for any instructor to easily and effectively adjust lesson components to suit his or her needs and circumstances given time, interests, and technology constraints. Introductory chapters provide useful information for the teacher about nanoscale science and technology and how they fit in with the study of the environment. Lessons are included which emphasize water quality and mineral-microbe interactions that provide background for later explorations that apply nanotechnology to environmental issues. Also included is a guide to using the curriculum and details of how the curriculum addresses the National Science Education Standards (NSES, National Research Council, 1996).

The Nano2Earth curriculum is based on a 5-E (engage, explore, explain, extend, evaluate) learning cycle model (Bybee, 1993), and included with each lesson are explicit details concerning how to support the activities using the 5-E cycle model. In addition, information is provided with each activity showing the lesson's alignment with the science content standards as stated in the *National Science Education Standards* (NRC, 1996). More detailed descriptions of how these standards are incorporated in Nano2Earth can be found in the curriculum booklet; an example is provided in Table 2.

Unifying Content and Processes

Nano2Earth is designed to assist students in making connections among the traditional scientific disciplines of biology, chemistry, earth science, and physics. For example, in the process of learning about groundwater pollution, students will explore the biogeochemistry of mineral-microbe interactions at the nanoscale. Within this context, students learn about the unifying concepts and processes as identified in the NSES (NRC, 1996, p. 113). The unifying concepts and processes include:

- Systems, order, and organization
- Evidence, models, and explanation
- Change, constancy, and measurement
- Evolution and equilibrium
- Form and function

Within the Nano2Earth curriculum, these concepts and processes include: (1) understanding the earth as an interconnected biological and physical system with different levels of complexity; (2) using evidence and mathematical modeling to interpret microbe-mineral interactions: (3) investigating change in biogeochemical systems under laboratory conditions; (4) using measurement and "scaling" from the macro to the nanoscale; and (5) examining how form and function apply to the interaction of bacteria with mineral surfaces.

Table 2. Excerpt from Nano2Earth describing the content related to the Unifying Content and Processes NSES.

The Nano2Earth curriculum explores nanoscale science and technology based on the theme of the role of mineral-microbe interactions on water quality. Student activities include observing iron reduction in solutions gathered from local creeks, ponds, or puddles, building a model Atomic Force Microscope from easily available lab supplies, interpreting AFM force curves of iron reducing bacteria interacting with various minerals, exploring the forces that control the migration and filtration of bacteria in porous media, and using concepts from previous activities in scenarios designed to apply to real-world problems (Table 1).

Lesson 1, "Introduction to Nanotechnology", probes the students' perceptions of large and small scale. Students are engaged through an activity where they are asked to label a logarithmic (power of 10) length scale covering many orders of magnitude with unlabeled arrows corresponding to a variety of distinctive lengths (Figure 1). For example, these lengths include the distance across the Milky Way Galaxy, a nanometer, the height of Mount Everest, the diameter of an atom, the diameter of a typical bacteria, etc. One question written by a Nano2Earth teacher is, "On the scale, is your height closer to Mount Everest or to a nanometer?" Mount Everest is only approximately four orders of magnitude larger than a typical human height, while a nanometer is nine orders of magnitude smaller! Students also learn about the history of nanoscience with excerpts from

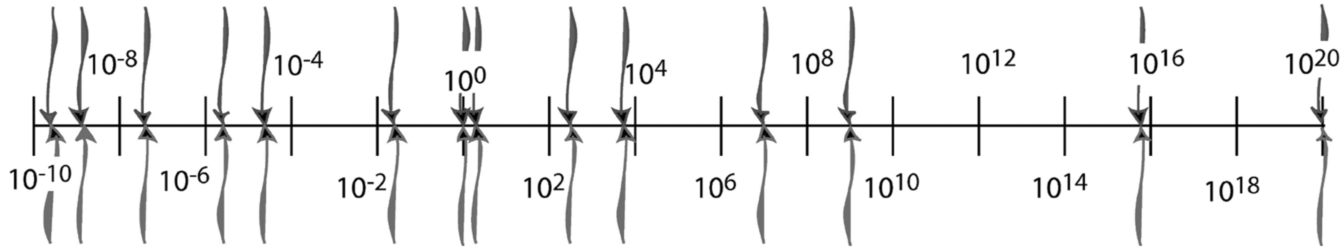

Figure 1. Excerpt from a Nano2Earth activity relating to scale. The numbers on the scale correspond to length or diameter in meters. The students fill in their guesses for various distinctive lengths above the top arrows, then fill in the answers afterward below the bottom arrows. From left to right, the answers are: diameter of an atom, nanometer, diameter of a DNA molecule, diameter of a typical virus, diameter of a typical bacteria, width of a human hair, length of a thumbnail, a meter, human height, height of the Empire State Building, height of Mount Everest, diameter of the Earth, diameter of the sun, a light year, and the distance across the Milky Way Galaxy.

Figure 2. Winogradsky columns from Blacksburg High School, showing before (left) and after (right) iron reduction. The dark appearance of the column on the left was due to suspended Fe(III) hydroxide nanoparticles. In the column on the right, supplementing with fertilizer caused the oxygen to be consumed faster, followed by the onset of iron reduction. During iron reduction, the solution became relatively clear as suspended Fe(III) was transformed to soluble Fe(II).

Richard Feynman's "There's Plenty of Room at the Bottom" lecture (Feynman, 1960). The potential influence of nanoscience on today's society as well as the future is brought to the students' attention when they elaborate on the current status of nanoscience by finding related current events.

What do I know about water pollution?	What do I wonder about water pollution?	What have I learned about water pollution?
Fertilizer runoff hurts the water	Is there a type of fertilizer that doesn't hurt the water?	Fertilizer-laden runoff causes algal bloom and eutrophication in farm ponds
Arsenic in water may be poisonous	What is the source of the arsenic? Is there arsenic in my water? Am I being poisoned?	
What does water pollution have to do with nanoscience?		

Table 3. Sample Know-Wonder-Learn (K-W-L) chart from Lesson 2.

Lesson 2 introduces the topics of groundwater and groundwater pollution. A series of demonstrations and activities provide a framework for both general and local water quality issues. The importance of water quality, the central theme of Nano2Earth, is explored through a water testing activity. The Know-Wonder-Learn (KWL) chart is introduced as a teaching and learning tool (see Table 3 for an example). The students are asked to look into local public water sources and contamination issues in their local community with a webquest activity and summarize their findings in a writing activity.

In Lesson 3, "Microbe-Mineral Interactions", teachers and students build small ecosystems known as Winogradsky columns using a local source of muddy stream, pond, puddle, or creek water (Figure 2). Ferric iron (Fe^{3+}) is added to the columns, and the students can observe color changes as the capped ecosystem becomes anaerobic, with concomitant reduction of ferric (red) to ferrous (green) iron. Color changes are correlated to dissolved oxygen measurements. The important concept of anaerobic microbial iron reduction is introduced and related to water quality. In addition, it should become apparent to the student that additional tools are necessary to actually observe and measure what is happening between microbes and minerals in the columns (i.e., nanotechnology!).

Another aspect of microbe-mineral interaction, vital to human health throughout the globe, is addressed in

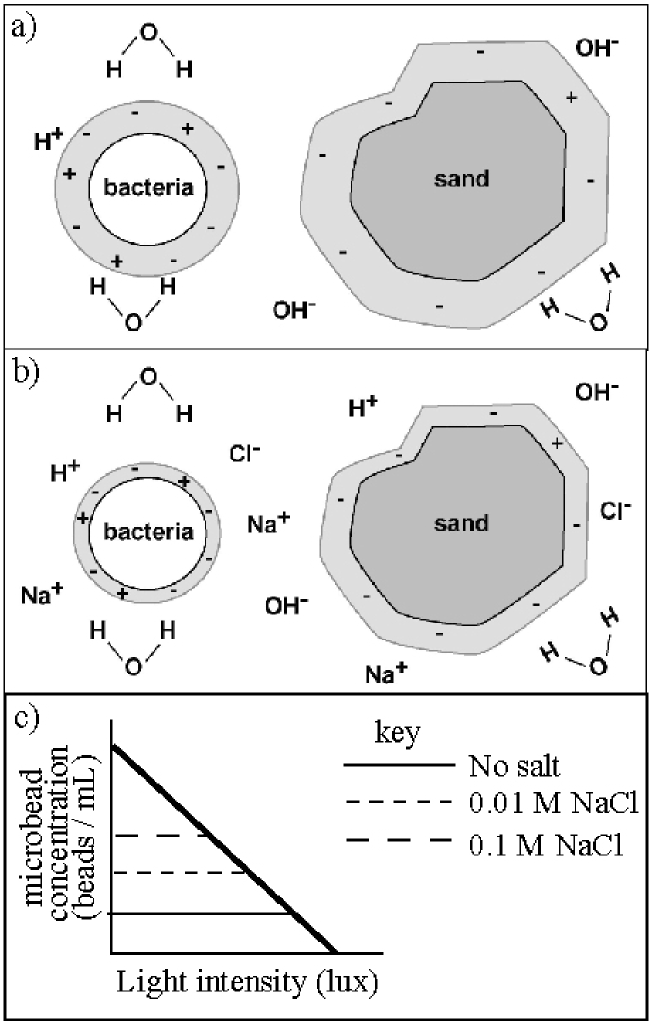

Figure 3 (a-b). Diagrams illustrating how changes in ionic strength can affect the charge distribution in the first few nanometers surrounding suspended particles, causing changes in their likelihood to stick together. These nanoscale surface properties are related to how pathogenic bacteria may be transported through groundwater. (a) In water not containing significant amounts of salt, both sand (quartz) and bacteria are typically negatively charged, preventing them from sticking. (b) When salts such as NaCl are added, positive ions like Na^+ can 'screen' the negative charge between the bacteria and mineral, allowing them to come together. (c) Schematic of how changes in ionic strength might affect the transport of beads (as analogues for bacteria) through a sand column, as measured by a CBL light sensing probe. The fluorescent beads absorb incoming light from a flashlight. As more salt is added, less beads are transported through the column, and the light intensity measured at the bottom of the column is higher.

Lesson 4, "Bacterial Transport in Groundwater". Easily assembled laboratory experiments investigate the role of nanoscale microbe-mineral interactions in removing simulated bacteria (microbeads) from a solution flowing through a sand column. This experimental setup presents ample opportunities for student creativity and inquiry, as a number of solution and solid phase characteristics can be varied (Figure 3). Students are asked to devise their own experiment and hypothesize how their chosen variable (ionic strength, solution composition, sand size, mineral type, etc.) might influence the transport of the microbeads through the column. Though microbeads are used rather than "nanobeads", this lesson emphasizes the nanoscale forces (on the order of nanoNewtons) which control interactions between particles and often determine whether or not they stick together. The experiments are easily adaptable to investigate the transport of fluorescent nanomaterials.

Finally, in Lesson 5, "Nanoforces in Nature", the Atomic Force Microscope (AFM) is introduced, along with applications of this nanotechnology tool to the previous lessons. Although AFMs are too expensive for a typical secondary classroom, the principles of how the AFM works are quite accessible and readily integrated into a physical model. Figure 4 depicts a schematic of an AFM, not drawn to scale. The corresponding model AFM shown in Figure 5 was developed by Nano2Earth teachers and can be constructed from materials readily or cheaply available. Lesson 5 leads students through the basics of how an AFM works and how it can be used to study microbe-mineral interactions, such as those observed in Lessons 3 and 4, by measuring the forces of interaction between bacteria and minerals (for example, Figure 6). Additionally, optional computer simulations provide additional avenues for students to learn about the AFM and its application to Earth and environmental science. Data for the AFM activities include actual data collected in our laboratory (Cail and Hochella, 2005; Lower et al., 2001) and data that was contrived for pedagogical purposes.

CHALLENGES IN INCORPORATING TECHNOLOGY-DRIVEN RESEARCH INTO A STANDARDS-BASED EDUCATIONAL MODEL

Often, research which is considered to be at the cutting edge takes advantage of continual advances in technology and analytical instrumentation. This technology is typically very expensive, such that access for educational purposes would be limited and require travel to a university or research laboratory. Thus only small numbers of students, and possibly only those enrolled in specialty science and technology programs, will be exposed to the technology. However, the technology and the principles behind it are central to the broader impacts of the science. This point is emphasized by the following comment about the necessity of atomic force microscopes to certain research activities in nanotechnology, as given by a participating scientist (Knefel, 2004):

> … I mean the reason they're doing it is because they've got the microscope that can do it. …you've got to have that fancy equipment…the scanning force microscope…to see at that scale, to measure at that scale. That's essential. You have to have it.

Thus, one major challenge for incorporating cutting-edge research into secondary science classrooms involves finding proxies for technology which are not currently available in the classroom.

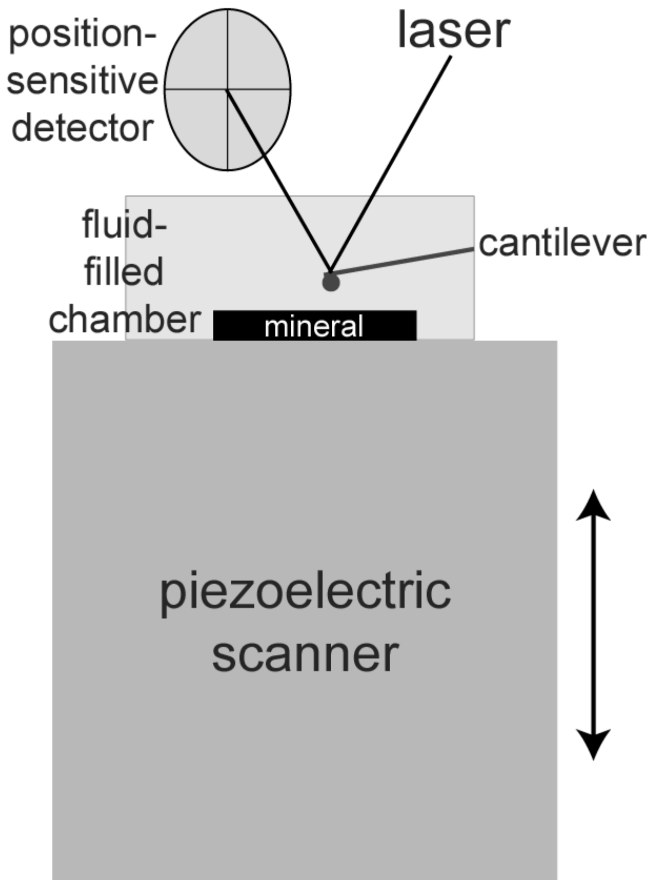

Figure 4. Schematic of how an Atomic Force Microscope works. A piezoelectric "scanner" moves up and down in response to an applied electrical signal; the motion can be controlled over length scales of ~0.01-5000 nm. A sample, in our case a mineral, sits on top of the scanner. A tiny flexible spring-like cantilever, analogous to a miniature diving board, is suspended slightly above the mineral. A sharp tip, bead, or other object may be placed on the bottom of the cantilever, such that it will interact with the mineral. The cantilever and mineral are contained within a fluid-filled chamber, allowing the solution conditions to be changed. A laser is directed to the back of the cantilever and reflected into a position-sensitive detector. As the bead (in this case) attached to the cantilever is attracted to or repelled from the mineral surface, the cantilever bends upwards or downwards, causing the position of the laser to move up and down when hitting the detector.

In this aspect, secondary science educators proved to be absolutely critical in the development of Nano2Earth. Teachers were given hands-on experience with an Atomic Force Microscope as directed by scientists, but it was a teacher who came up with a model AFM design that could be built very cheaply with simple materials (Figure 5). Additionally, teachers suggested the use of computer-based laboratory (CBL) probes for sensing light, pH, and dissolved oxygen. Also, teachers suggested the use of computer simulations for providing an additional visual and conceptual model for the AFM and collection of AFM force curves related to environmental problems.

1. Fiscal support
2. Long-term commitment
3. Clear focus
4. Manageable agenda
5. Process assessment and program evaluation
6. Involve institutions within easy driving distance
7. Mutual self-interest and common goals; each party must be selfless enough to assure the satisfaction of these self-interests
8. Mutual trust and respect
9. Set aside politics and turf issues in favor of reaching common goals
10. Commitment from top leadership; seek new leaders to replace lost ones
11. Dynamic nature, both of project goals and leadership structure
12. Information sharing

Table 4. Summary of the characteristics of successful scientist-educator partnerships.

An additional barrier to the inclusion of new materials in established curricula is the current educational reform which mandates an increasingly standards-based system of secondary student and teacher evaluation. Although the *National Science Education Standards* (NRC, 1996) are characterized by rather generalized concepts that allow a great deal of instructor flexibility, students and teachers are in actuality evaluated based on state standards which contain very specific components. Concepts and innovations involving the latest technological advances and equipment are not included on the end-of-course tests dictated by the course content standards. Thus, any time spent on content not directly addressed by the standards may cause a drop in student test scores.

Because the high school science course content standards drive the curriculum in our state, the development of Nano2Earth proceeded through the lens of the Virginia Standards of Learning (VA SOLs). Before curriculum brainstorming sessions, teachers who were intimately familiar with the SOLs from their various content areas presented materials on the VA SOLs to provide a framework for the scientists. Another advantage of including an interdisciplinary group of teachers was that they could guide and correlate lessons to maximize overlap with the standards. Despite all of these efforts to accommodate a standards-based model, many teachers who were contacted to test Nano2Earth in their classrooms agreed to do so only during the portion of the school year after their students had taken the end-of-course SOL tests.

K-12 and university educators were also able to give perspective and experience for dissemination, both in the format and type of materials (i.e., book, CD, websites) along with the content of presentations. Scientists presenting cutting-edge research to audiences of K-12 teachers typically can relate their work to broader societal issues, but gloss over the biases implicit in their research (Glasson and Bentley, 2000). Educators and scientists participated together in poster, panel, and classroom presentations to international, regional, and local groups such as the Geological Society of America annual meeting, the Virginia Association of Science Teachers, and high school classrooms.

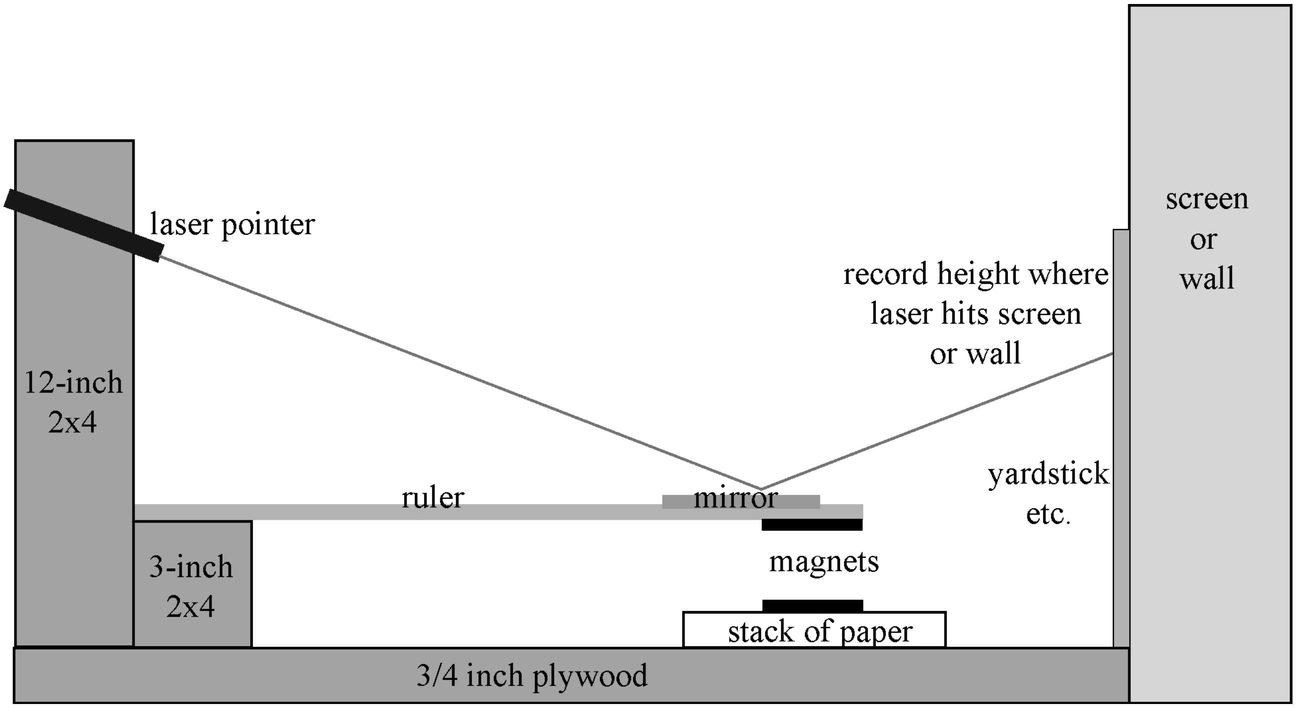

Figure 5. Schematic for a model Atomic Force Microscope (AFM) developed by a Nano2Earth teacher that can be built by the students. A magnet is taped to the bottom of the ruler. Another magnet is placed below such that its height can be adjusted, for example by adding or removing sheets from a stack of paper. If the magnetic poles are oriented N-S, the attractive force will bend the ruler downward. As the ruler flexes upwards or downwards, the laser reflecting off of the back of the mirror moves simultaneously on a wall. The position of the spot can be determined with a yardstick (the distance from the AFM and wall/screen can be increased to add sensitivity). If the magnetic force is repulsive, the ruler will bend upward. This is analogous to the collection of force-distance data or 'force curves' using an AFM.

CHARACTERISTICS OF SCIENTIST-EDUCATOR PARTNERSHIPS, THE DEVELOPMENT OF NANO2EARTH, AND RELATION TO EXISTING PARTNERSHIP MODELS

In order to use the experiences of the contributors to Nano2Earth project to provide general helpful hints to scientists and educators who may be working in partnerships so that they may be better able to address similar issues to the broader impacts criteria, a comparison of the Nano2Earth partnership to other scientist-educator partnerships is warranted. Much has been written about both general models and specific examples of college/university - K-12 relationships. The term "partnership" has been used to describe a wide variety of associations between colleges/universities and K-12 programs, including 1) programs and services for educators, 2) programs and services for students, 3) coordination, development, and assessment of curriculum and instruction, and 4) programs to mobilize, direct, and promote sharing of educational resources (Carriuolo, 1996; Clark, 1999). A single model will not fit all successful partnerships; however, those that flourish seem to have some commonalities. Table 4 summarizes the findings of several authors that have reviewed and delineated the characteristics of successful scientist-educator partnerships (e.g., Goodlad, 1998; Gomez et al., 1990; Carriuolo, 1996; Verbeke and Richards, 2001; Hall-Wallace et al., 2003; Sirotnik and Goodlad, 1998). Consistent with the 12 success criteria in Table 4, the Nano2Earth project fulfilled most of the criteria throughout the life of the partnership, from its initial conception to the final field testing of the activities and evaluation of the project.

Criteria 1-4 (fiscal support, long-term commitment, clear focus, manageable agenda) - As part of an NSF grant, the project funding, duration, and expectations were explicitly laid out by the scientists and university educators in the grant proposal. The university educators played a lead role at this early stage of the partnership because through their combined experiences, they were able to provide a reasonable project focus from which a practical agenda were delineated. In addition, the university educators' previous experiences provided the fiscal and logistical expertise needed when discussing compensation for the high school teachers, the plans for group meals which proved beneficial for team building and project success, contracting for technical needs, travel for all participants, the developments of software, and the production of materials for testing and dissemination. As such, the significant fiscal contribution of the NSF research grant to the outreach component greatly contributed to project success. Out of the $1M research grant, the financial support for educational and outreach activities was approximately $100k. A vast majority of research grants will have significantly less money available for scientist-educator partnerships. We would predict that similar criteria to those presented here would still be applicable to success of a project with less financial support. One great advantage to a scientist-educator

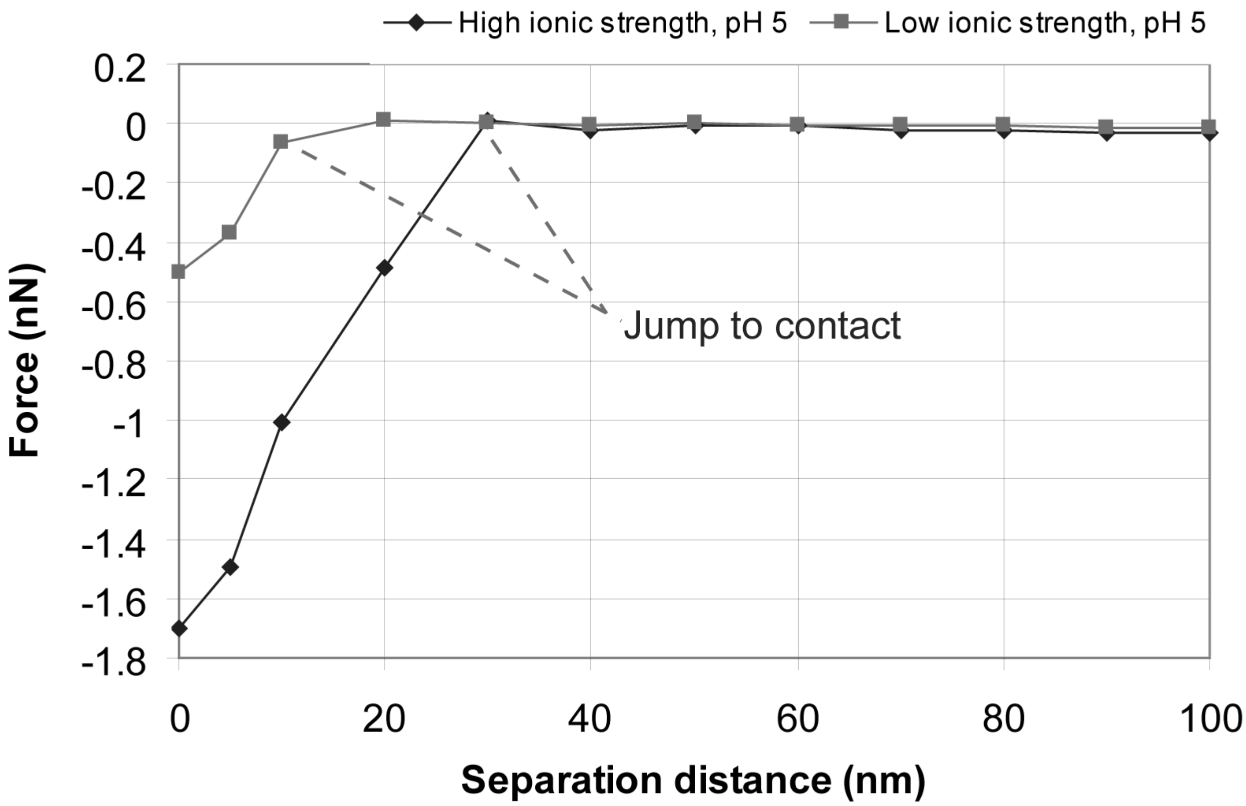

Figure 6. Data for the simulation of AFM force curves. The situation is similar to that described in Fig. 4, with a bead covered in bacteria attached to the bottom of the cantilever. The distances are in nanometers and the forces of attraction and repulsion are much smaller, in nanoNewtons and are not due to magnetism, but rather interatomic forces. The graph, representing the approach of the bacteria-coated bead and the mineral, is read from right to left, starting at the point where the bead and mineral are farthest apart (100 nm). As they are brought together, the forces of interaction are close to zero. At some distance, the bacterially-coated bead and mineral experience enough attractive force that they start to snap together, the 'jump to contact'. The jump to contact occurs at different distances for high ionic strength (diamonds, high salt content) and low ionic strength (squares, low salt content). In this case, the attractive force begins at larger separations in high ionic strength solution, suggesting that the bacteria will be more likely to stick to the mineral as the salt content increases. Also, the magnitude of the attractive force (negative numbers imply greater attraction) is greater for the higher ionic strength when the bacteria and mineral are in contact.

partnership is that the partners together will be able to provide a much more realistic impression of what can be accomplished with a given budget as compared with either group alone. Thus, the financial component should be a consideration at the conception of the partnership. A long-term commitment has been demonstrated through continued efforts beyond the initial grant proposal funding period (in this case four years).

Criterion 5 (process assessment and program evaluation) - Mechanisms for process assessment and program evaluation were formulated very early in the life of the project and implemented throughout the project by an external assessor from the Sociology Department at Virginia Tech. These mechanisms involved one-on-one interviews with all educators and scientists to ascertain their feelings and perceptions about their involvement in the partnership, as well as their ideas about the project goals and progress.

Criterion 6 (Involve institutions within easy driving distance) - Solicitations for outstanding secondary science and math teachers to participate in the project were directed to regional school districts relatively close to the university. The partner secondary teachers had to commute at most 40 miles on excellent highways to attend meetings at the university. While this commuting distance was not ideal, it did not appear to interfere with the participants fostering and maintaining a solid scientist-educator partnership throughout and beyond the life of the project.

Criteria 7-8 (Mutual self-interest and common goals, each party must be selfless enough to assure the satisfaction of these self-interests, mutual trust and respect) - From the experience of the Nano2Earth project, mutual self-interest, common goals, selflessness, trust, and respect grew among the members of the partnership from the time spent together with participants as a large group, as well as from working in the smaller, activity-based teams. A majority of Nano2Earth was developed through a series of workshops, approximately 3-4 days in length, during which project members gathered, either as a whole or in subsets, at various times throughout the four-year funding cycle. The pool of candidates crossed disciplines, levels of teaching experience, and experience with curriculum development projects.

The purpose of the initial workshop was primarily to provide educators with opportunities to learn about nanoscale science and technology and to participate in university-level hands-on laboratory activities. After general introductions and a discussion of project goals, the first day consisted of scientists speaking to the group about technical aspects of their research programs. The scientists had little experience presenting to this type of audience. In retrospect, this was not the most effective strategy, as evidenced by the comments of one teacher:

> They tried to break it down enough but you have to really be sort of trained in that stuff to really understand…the complexities of it. And, we're not trained in it. I have a little understanding given my background but it's so technical and I've been out of the game for so long that I can't really remember.

(Throughout this section, quotations are drawn from transcriptions and notes included in Nano2Earth assessment reports (Knefel, 2005)). However, the remainder of the three-day workshop largely focused on hands-on laboratory experiences in nanoscience and nanotechnology specifically designed for the teachers. Overall, the teachers enjoyed having an opportunity to work with scientists on the equipment, but expressed interest for a more authentic laboratory experience. The workshops were initially limited to the summer to best accommodate the availability of the participants, with only intermittent contact between workshops.

The second summer workshop used the activities of the previous years' workshop as a foundation to begin the actual construction of lesson plans. During this three-day workshop, educators presented their perspectives about the 5-E pedagogical model, the state and national science standards, classroom diversity issues, and other topics that the educators felt were relevant for the partners before committing more time to developing the curriculum. Part way through the workshop, the focus shifted to discussions that revolved around brainstorming lesson ideas posed by both scientists and educators. After the brainstorming sessions, the team split into two groups and generated more in-depth ideas about the Nano2Earth curriculum ideas. The secondary science educators played a lead role in lesson development, as evidenced by these comments by an educator (first) and scientist (second):

> One thing I like about this time…is that we were actually in the lab experimenting and trying to come up with ways of doing this, [some of which] didn't work, so we had to go a different way [than] we were thinking [about] how we're going to do the lab. And we're thinking this is what [will] come out of it, and then we completely changed it around because we got in the lab and we actually worked with the scientists and changed methods. I really enjoyed being in the lab and actually doing the lab.

> …the teachers had a much stronger role in what was going on this year. Last year, they were more like students, and we were teachers. Now, it's more equal.

In addition to alternating scientists and university educators as discussion facilitators, planned social activities were key to developing a strong enough relationship to commit people to the project (criterion 7) and develop mutual trust and respect (criterion 8). This is exemplified by the following statement by a teacher:

> And the difference is, and I've worked on other projects where there were scientists that were there for us to ask questions. But, I think one of the differences here is that, since they've been with us all week then we've established a relationship, so we feel, I feel comfortable talking with them. Some other projects that I've worked on, there might have been scientists affiliated with the project but they haven't been with us and eating lunch with us and been with us the whole time and so, you always felt a little uncomfortable.

In order to develop and maintain trust between scientists, secondary teachers, and university educators, continued involvement of the teachers in curriculum development and conference presentations was essential. The established trust and mutual respect was evident in the comment voiced by one of the participating high school teachers:

> Plus, I've worked on projects where the scientists had very little value for the pedagogy, and they actually would go back and change things that I had done that had to do with the teaching of it which I thought was inappropriate, and very inappropriate. And these scientists are…very respectful [of] our knowledge of teaching and the knowledge of our students.

Criterion 9 (Set aside politics and turf issues in favor of reaching common goals) - Personal agendas and departmental/institutional goals may not always match between all members of a partnership. The delegation of responsibility, effort, and credit may be suboptimal due to the perceived need for individuals to defend their 'home turf'. In this regard, the participation of graduate students can be beneficial. The role of science graduate students has been judged to be critical in other K-12 / university partnership studies (Tomanek et al., 2005). In the Nano2Earth project, graduate students in both the Departments of Geosciences and Teaching and Learning were also heavily involved and made significant contributions to the development of the curriculum. One major result of the participation of graduate students relates to criterion 9. Graduate students are transient; as such, they tend to be less bound by institutional and individual politics. For the duration of graduate studies, turf issues are much less important than achieving the project goals. By becoming heavily involved in the partnership, it is also in the best interest of the students to see through the success of the project for both emotional and career-oriented reasons. In addition to helping to assist in the success of specific outreach and educational activities, science graduate students play an important role in the forming of a new generation of scientists who are experienced in addressing "broader impacts" through the formation of partnerships with university educators and teachers (Tanner and Allen, 2006).

Criteria 10-11 (commitment from top leadership; seek new leaders to replace lost ones, dynamic nature both of project goals and leadership structure) - The commitment and dynamic nature of the project leadership was demonstrated through the grant principal investigators. The principal investigators participated in varying degrees when their particular talents and experience were most needed. Principal investigators participated in brainstorming and workshop sessions, organized meeting and social activity agendas, presented at regional and national science and educational conferences promoting Nano2Earth, wrote curriculum for Nano2Earth, and made contacts NSF for advice with dissemination of the curriculum. This continuous involvement and commitment by the principal investigators proved beneficial when the leadership structure had to be redesigned when one principal investigator relocated out-of-state. Throughout the project, the effort experienced the loss of one of the contributing scientists and the public school math educator. However, an additional public school teacher joined the partnership. Overall, the minimal change in the people involved with the partnership contributed to a stable membership, as well as a shared history including the necessary content background, focus, and goals.

Criterion 12 (information sharing) - Despite the multiple gatherings of participants throughout the course of the project, the nature and extent of communication between team members received criticism from internal and external reviews. Additional mechanisms for communication and contact should be initiated early on in team building, and they should be utilized frequently. Although each participant had access to contact information of all parties involved, some scientists and educators alike would have liked additional general updates and information-sharing during the year between large summer gatherings. Suggestions for improvement include designating someone to send a regularly scheduled update email / letter and/or the creation of an email listserv of all participants with encouragement to use it.

CONCLUSIONS

The U.S. National Research Council's program entitled "Resources for Involving Scientists in Education (RISE)" caution strongly against scientists who attempt to develop curricular materials without the intimate participation of education experts.

> Unlike the other roles for scientists discussed in this site, a role in developing instructional materials for K-12 science education is suitable only for a few individuals. Many of those involved in improving science education advise scientists who are interested in developing materials, "DON'T DO IT!!"…The working conference participants who discussed this role agreed that, "The proliferation of "home grown" scientist-teacher content modules may be deleterious to our overall goals of teaching and disseminating good science. Opinions on this subject are often strongly colored by our values, personal goals, and limited experiences." (http://www.nas.edu/rise/roles4.htm).

Due to the implementation of policies such as NSF's broader impacts criteria, scientists are under increasing pressure to become involved in outreach and education projects. By seeking out education and outreach professionals from their academic communities, scientists should endeavor to participate in scientist-educator partnerships. Although there are perceived and real cultural and professional barriers to successful scientist-educator partnerships, suggested guidelines from past projects help to provide a framework for project success. Such a framework, constructed from the work of multiple authors (Table 4), was employed to evaluate the Nano2Earth partnership in an effort to elucidate the strengths and weaknesses of the partnership. Through this systematic and purposeful examination of the characteristics of a scientist and educator collaboration for broader impacts activities, the dynamics of the Nano2Earth partnership that led to its success became more transparent. However, instead of waiting until the end of the project, if this assessment can be conducted throughout the conception and throughout the life of the partnership, principal investigators can take action leading to more successful and productive relationships between the educators and scientists.

Scientist-educator partnerships can be "win-win" scenarios for all involved if the partnerships are a success in terms of participants' relationships and final products. The creation of scientist-educator partnerships has the potential to benefit society (the goal of the "broader impacts" criteria) by the creation of higher-quality and more useful end products. The involvement of a new generation of graduate students is important, in that they will be more aware in their future careers of the value of scientists and educators working together. Practicing teachers and their students benefit by the teachers' enhanced science content knowledge and understanding of cutting-edge science.

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