SECTION D - PROJECT DESCRIPTION

Rationale

The revolution nanoscience brings to diverse areas of human endeavor—including medicine, industry, and environmental management—requires a commensurate response in the educational community to increase students' understanding of core concepts in the field. Whereas numerous nanoscale science and engineering programs exist at the undergraduate and graduate levels, there is a strong need for nanoscience education in earlier grades, both to increase students' scientific literacy and to prepare them for further study in the field. Including nanoscience education in the high school curriculum would do more than bring nanoscience concepts "down" to the high school level. It would also introduce a much-needed interdisciplinary element into the disjoint high school curriculum, since nanoscience brings together concepts from physics, chemistry, and biology, as well as related areas such as materials science and engineering. It would provide a way to revisit the core concepts from these domains and view them through a different lens. Nanoscience education can support understanding of the interconnections between the traditional scientific domains, reflecting the "unity in nature" (Roco, 2003), and can provide compelling, real-world examples of science in action.

Two conceptual areas are likely to pose the greatest challenges to understanding of core nanoscience concepts for students at the high school level. The first of these arises because nanoscale entities are generally difficult to visualize or see. A large number of studies, mostly focused on chemistry learning, document the problems students have understanding the behavior of atoms and molecules (e.g., Bunce & Gabel, 2002; Nakhleh, 1992; Wu, Krajcik, & Soloway, 2001). Understanding processes that involve creating and using nanoscale entities will, we believe, pose similar difficulties for students. The second challenge to student understanding results from the concepts and physical laws that govern the behavior of particles at the nanoscale level. Everyday, "macro-level" experience of how physical objects move and interact can quite accurately be described by Newtonian physics. However, at the nanoscale level, different rules predominate. Gravity becomes negligible, while coulombic forces, quantum mechanics, and the random thermal motion of particles become central considerations. Generally, there is little in students' experience of the physical world and their intuitive conceptions regarding aggregate matter that can apply directly to conceptualizing nanoscale phenomena.

The materials we propose to develop in order to address nanoscience education needs at the high school level build on previous efforts in our NSF-funded ChemSense project (REC-0125726). ChemSense includes a collaborative chemistry visualization environment (see Figure 1) and more than 40 associated standards-based, high-school-level curricular activities.[1] The goal of the ChemSense project is to help students understand chemical concepts by providing access to rich representational tools that help them visualize the world of molecular entities and reactions (Schank, Michalchik, Rosenquist, & Coppola, 2003; Schank, Kozma, & Coppola,

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[1]One or more high school ChemSense activities exist for the following topics: Matter, atomic theory, stoichiometry, solutions, gases, thermodynamics, periodic table and trends, orbital diagrams, bonding, molecular forces, polarity, equilibrium, rates of reaction and kinetics, acid-base, electrochemistry (oxidation/reduction), and organic chemistry. Examples include "Water Wiggles" (students animate water molecules as they change temperature and phases from ice to gas, and correlate each frame with relative position on a phase change graph) and "Acid-Base Dissociation" (students represent acids and bases as they dissociate and release hydrogen and hydroxide ions). Activities are available at http://chemsense.org/classroom/activities.html.

2002). ChemSense makes it possible for students to create—individually or collaboratively—and share—face-to-face or virtually—representations such as drawings and animations of nanoscopic phenomena in a way that readily affords knowledge building in the classroom.

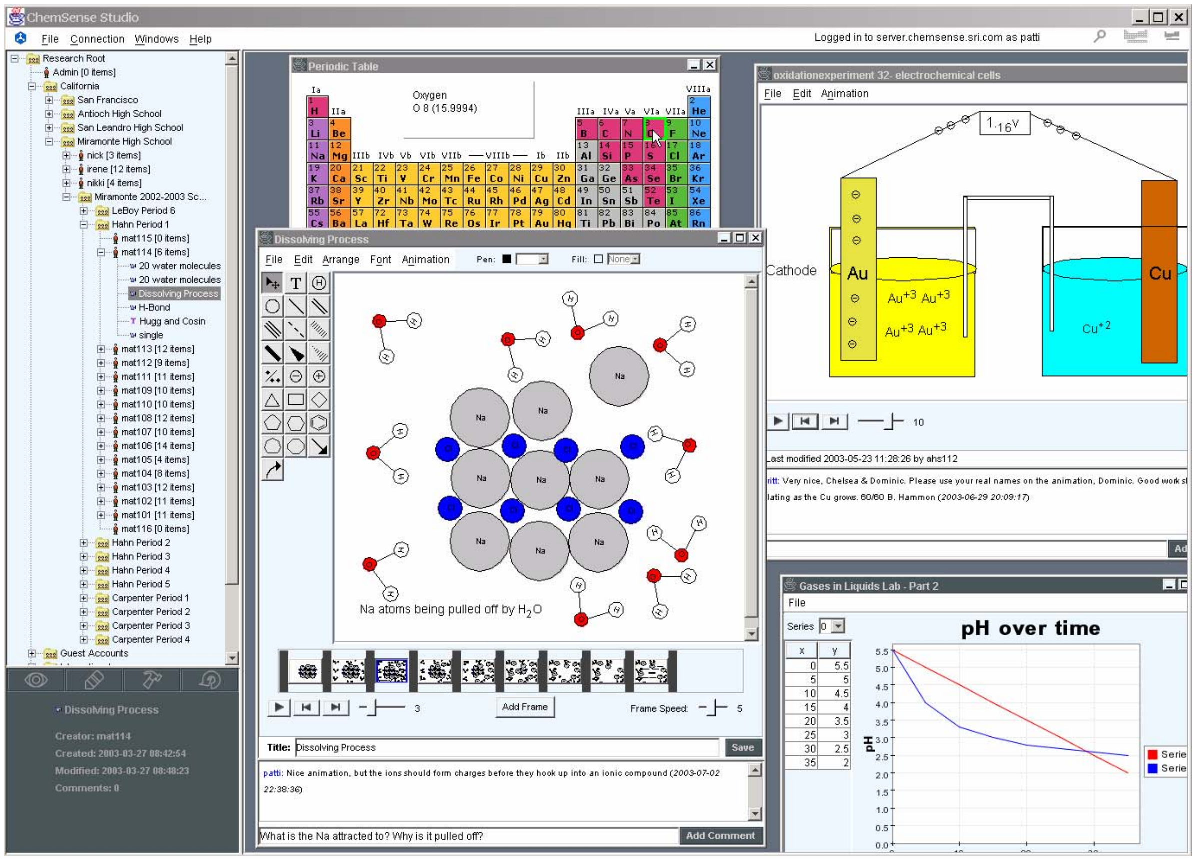

Figure 1. The *ChemSense Studio* with item browsing area (upper left), preview pane (lower left), and workspace. The workspace shows sample high school student work.

Over the past 2 years, ChemSense has been used by more than 700 students in 24 high school classrooms and by more than 40 high school teachers in summer professional development workshops. Our research on the effects of ChemSense indicates the value of visualizations for enhancing students' understanding of the behavior of particulate entities (Michalchik et al., 2003). Research on other visualization tools and strategies also shows the significant impact visual representations can have on students' understanding of complex scientific concepts, both in the domain of chemistry (e.g., Barnea & Dori, 1999; Burke, Greenbowe, & Windschitl, 1998; Copolo & Hounshell, 1995; Sanger & Badger, 2001; Wu et al., 2001) and in other scientific areas (e.g., Mayer, 2003; Suthers & Hundhausen, 2003; Goldman, 2003; Roth, 1996). Difficulties that students may have in understanding and learning from visualizations can often be overcome with appropriate scaffolding (Barnea & Dori, 1999; diSessa & Friedman, 1999; Roth & McGinn, 1998), particularly if students themselves generate or manipulate the representations (Gobert & Clement, 1999; diSessa, Hammer, Sherin, & Kolpakowski, 1991; Kelly & Crawford, 1996). Further, the shared construction of representations by a variety of means, including networking tools (Chan, Burtis, & Bereiter, 1997; Roth, 1996), help students "make connections among perspectives, ask questions of one another, and observe their revisions over time" (Herrenkohl, Palincsar, DeWater, & Kawasaki, 1999). Building and acting on shared knowledge, particularly when embodied in representations, provides learners with the opportunity to align their attention, coordinate their perceptions, and converge their ideas about the scientific explanations they construct. The particular value of the ChemSense tool lies in how it readily affords students the means to generate and share representations, causing students to make and justify specific design choices (e.g., as they create stepwise animations) to their peers and teachers. To make their own design decisions, students need to think critically about the entities and processes they are representing.

Visual representations created in ChemSense also serve as a ready means for formative assessment. By design, student thinking becomes "visible" in ChemSense through the creation of representations. In our prior research with ChemSense, teachers felt they could better assess their students' understanding and provide timely and targeted feedback by simply walking around the classroom and viewing students' visual representations on the computer screen.

By focusing on providing tools, activities, and assessments in an integrated curriculum to allow students to create their own visual representations of nanoscale entities and phenomena, the ChemSense-based materials we plan to develop will complement other current approaches to nanoscience education. These other approaches—such as the NSF-funded Interactive Nano-Visualization for Science and Engineering Education (IN-VSEE) project (Ong et al., 2000) and efforts using the *nanoManipulator* tool (Jones, Andre, Superfine, & Taylor, 2003)—provide students with important opportunities for interacting with nanoscale entities. These types of educational experiences would be enhanced by the opportunity for students to use an expressive tool such as ChemSense to represent their conceptual understanding of scientific phenomena at the nanoscale level.

Goals and Objectives

The goal of this project is to promote the learning of science concepts that account for nanoscale phenomena. Though these concepts do not represent new scientific understanding, per se, the characteristics and properties of substances exhibited at the nanoscale level is a relatively new focus. We will work closely with chemists, educators, and nanoscientists to generate a set of nanoscience activities that build on ChemSense. These units will help students visualize physical, chemical, and biological principles that govern the behavior of particles on the nanoscopic scale. We will extend our curricular framework, software, and activities to help students conceptualize underlying principles and will test the effectiveness of the materials. This work will allow us to examine questions such as: Will students' understanding of nanoscience concepts improve over time? For example, will their understanding of the effects of size and the forces that apply at nano (versus macro) scales improve? Will they understand the significance of high surface-to-volume ratios and the surface dominance of reactions at the nano scale? Will students' ability to understand the applications of nanoscale engineering improve over time? Will they appreciate how technologies can alter their lives and society? Will they understand the interplay between science and technology? How do teachers use these tools and activities to support student discourse and understanding?

Instructional Materials

Content. Our team of educators and nanoscientists will develop a set of curricular activities that focus on real-world examples of nanotechnology and the underlying scientific concepts, such as those identified by Drexler (1992, 1988) in his analysis of the fundamental content areas important to nanotechnology: mechanics, electromagnetism, thermodynamics, and quantum mechanics. We will extend our existing curricular framework and create, classroom test, and refine 12 to 15 nanoscience activities that draw on concepts from physics, chemistry, and biology. Some of our activities will be simple 1-day enrichment activities; others will be more highly developed units that may span two to four class periods. Some may include multiple modules from which the teachers can select.

Table 1 presents examples of nanoscience activities that we propose to develop. Each activity is presented with associated mappings to nanoscience topics, traditional high school topics, and applicable standards. These topics, generated through discussions with four SRI nanoscientists and other partners in this effort, do not duplicate any of our existing ChemSense activities, which focus solely on traditional chemistry activities. The proposed activities would reflect the interdisciplinary nature of nanoscience; emphasize fundamental nanoscience concepts such as size and scale, and surface dominance of reactions; and explore applications of nanoscience and how they could affect society, policy, and students' lives. The ordering in which the activities are presented is not meant to imply a required ordering; teachers of various disciplines (chemistry, biology, physics, interdisciplinary science) would be able to choose subsets of activities as they relate to topics they may already address.

Materials. Each module will include professional development materials for the teacher, activities and instructional materials for students, and embedded formative and summative assessments and rubrics. Professional development materials will provide background information that explains nanoscience concepts and applications pertaining to each activity, resources related to the activities, and links to applicable National Science Education Standards (NSES) Grades 9-12 Science Content Standards. Materials for the students will include an activity guide with instructions on how to carry out the nanoscience activity, a specialized vocabulary list particular to the activity, worksheets developed to summarize and reinforce major concepts, and embedded formative and summative assessments and their associated scoring rubrics. There will be a *Teachers Guide* correlated with all student forms. The *Teachers Guide* will include guidelines for schedule, background information that students should know to be able to participate fully in the activity, and any specialized preparation instructions. Each learning activity will also have a variety of instructional materials for the teacher to introduce the traditional curricular topics and key nanoscience concepts that the activity is exploring. These materials will take the form of background reading, video clips, news articles, slides, and handouts, available on CD-ROM and on our Web site. Materials will be provided in browser-friendly, nonproprietary formats (e.g., HTML, PDF) to maximize accessibility.

Pedagogy. Our pedagogical approach will emphasize the importance of selecting activities that are appropriately challenging and relevant to students' experiences, student generation of representations of nanoscale phenomena, multiple opportunities for scaffolded discourse and peer review, and collaborative project-based investigations (Krajcik et al., 1998). Teachers will use our materials to introduce the students to key concepts related to the topic area, and then students will engage in learning activities in which they pose questions, conduct investigations, analyze data, create models, and present findings. Each stage of this process will promote and benefit from student discourse and use of representations. We will also consult with nanotechnology experts and use other resources to build a conceptual framework that ties together significant concepts in nanoscience and is linked to national and state standards. Our framework will provide teachers with a conceptual map of key nanoscience concepts and candidate activities, assessments, and scoring rubrics. We will conduct workshops to train teachers on the use of the tools and to refine activities, assessments, and other materials.

Table 1. Candidate activity topics, with mappings to nanoscience topics, traditional high school topics, and the National Science Education Standards (NSES) 9-12 Science Content Standards.

Sample Activity	Sample Related Topics	Sample NSES
Size Matters. How small is nano? Contrast sizes of objects (e.g., hair, cell, nanoparticle); present examples of "old" nanotechnologies like nanogold (stained glass windows, glazes); discuss evolution of scientific perspectives (e.g., Newtonian to quantum mechanics) and unusual properties of the nanoscale.	*Nanoscience.* Size and scale; quantum mechanical effects. *Physics*. Newtonian vs. quantum mechanics; thermal vibration; scaling laws. *Chemistry*. Atomic structure; molecular-kinetic theory of motion. *Biology*. Size of cells and their components. *Interdisciplinary*. Historical perspectives; the four fundamental forces; size and scale.	Historical perspectives; structure of atoms; structure and properties of matter; the cell.
Nanoscience in Your Life. How could nanotechnology change your life? Discuss nanoscience in the news, present examples of existing applications (e.g., sensing proteins via quantum dots, new clothing materials, cosmetics) and speculate on future uses of nanotechnology (e.g., molecular electronics, medicine).	*Nanoscience.* Nanopowders; surface-to-volume ratios; optical and electrical properties. *Physics*. Optics; conductivity; circuits; magnetism. *Chemistry*. Atomic and molecular structure and interactions; solution chemistry; catalysts. *Biology*. Cellular components; gene technology; proteins; metabolism. *Interdisciplinary*. How technologies may alter our lives; ethics.	Science in personal and social perspectives; structure and properties of matter; understanding about science and technology.
Nanotechnology Controversies. Discuss controversies (e.g., are molecular assemblers possible?), potential environmental impacts of nanomaterials, and how science fiction can scare the scientifically illiterate (e.g., the gallium arsenide-based creatures in *Prey* would be toxic to organic hosts and can't be replicated biologically).	*Nanoscience*. Self-assembly; self-replication; nanofabrication; environmental impact concerns. *Chemistry*. Solution chemistry; molecular forces and interactions. *Biology*. Self-replication; self-assembly correlations to protein synthesis; genetic engineering. *Interdisciplinary*. Ethics; critical thinking; the interplay between science, technology, economics, government, and public perception.	Understandings about scientific inquiry; science and technology in local, national, and global challenges; matter, energy, and organization in living systems.
Biomolecular Motors. Biology is full of nanomachines that convert chemical energy into mechanical work (e.g., bacterial flagella, cilia, myosin, ribosomes). Can man-made nanotechnology mimic nature's machines or harness them to create new, useful devices?	*Nanoscience.* Self-replication; self-assembly; nanobiotechnology. *Physics*. Mechanics; work; efficiency. *Chemistry*. Catalysis. *Biology*. Molecular biology; protein synthesis; muscle fibers; self-replication; enzymes. *Interdisciplinary*. Biological analogs to man-made machines.	The cell; matter, energy, and organization in living systems; chemical reactions; understanding about science and technology.
Tools of the Nanosciences. Survey techniques for *seeing* atoms (e.g., scanning probe microscopy) and *manipulating* nanostructures (e.g., electrochemistry, nanolithography, self-assembly, crystal growth). These tools interact with the structural, electronic, or magnetic properties of	*Nanoscience*. Nanometrology; self-assembly. *Physics*. Measurement of force, voltage, and current. *Chemistry*. Electrochemistry; crystal structures. *Biology*. Observation of cells; microscopes (STM, EM, light). *Interdisciplinary*. Leaps in commercial technology correlate with leaps in tool	Understanding about science and technology; motions and forces; interactions of energy and matter.

surfaces and enable the nano age.	inventions.	
Quantum Dots. Nanocrystals called quantum dots can emit differnt colors of light depending on the material type, size, and spacing. Nanogold, for example, can appear orange, red, or green depending on the size and spacing of the gold atom aggregates. Quantum dots can be used as fluorescent labels in biological imaging and drug discovery research.	*Nanoscience.* Size and structure determine optical properties. *Physics*. Electromagnetic waves; energy; reflection and refraction of waves (optics). *Chemistry*. Atomic structure; crystal structure; absorption and emission of light; physical, chemical, and magnetic properties; surfactants. *Biology*. Diagnostic labeling and imaging.	Interactions of energy and matter; structure and properties of matter.
Nano Pants. Manufacturers are using fine-spun fibers to confer stain resistance on khaki pants and other products. Why are some spills (e.g., wine) easier to repel and others (e.g., oil) more difficult to repel?	*Nanoscience*. Nanomaterials. *Physics.* Electrical attraction and repulsion. *Chemistry*. Intermolecular (e.g., hydrogen) bonding; solution chemistry (miscibility). *Biology*. Hydrophobic and hydrophilic properties; selective permeability; micelles.	Structure and properties of matter—bonding;
Clear Sunscreen. Old sunscreens use “large” zinc oxide particles, which block ultraviolet light but scatter visible light, giving the cream a white color. If nanopowders of zinc oxide are used instead, the cream is transparent, because the diameter of each nanoparticle is smaller than the wavelength of visible light.	*Nanoscience*. Nanopowders; quantum dots. *Physics*. Optics; absorption of light; electromagnetic spectrum and associated wavelengths, frequencies, and energies. *Chemistry*. Electromagnetic spectrum; colloidal solutions. *Biology*. Ultraviolet radiation; cell damage.	Interactions of energy and matter—electromagnetic waves; the cell.
Carbon Nanotubes. Cylindrical nanotubes can be excellent electrical conductors. Mixed in polymers in tiny amounts (e.g., 1%), they frequently touch and make the composite conductive. Nanotubes could also be used to make tiny nanogears, as well as filters to separate molecules.	*Nanoscience*. Nanomaterials; electrical, magnetic, and conducting properties of nanoscale objects; the impact of shape. *Physics*: Conductivity, uncertainty principle. *Chemistry*. The allotropes of carbon; superconductors and semiconductors; physical and chemical properties; bonding.	Interactions of energy and matter—conductors; structure and properties of matter—carbon, bonding.
Solar Cells. Nano solar cells could be made by embedding photoactive nano rods in a polymer layer between two electrodes. Light excites the electrons in the rods to create a current that is carried away by the electrodes. Nano solar cells may some day be painted on surfaces so almost anything could be a solar collector.	*Nanoscience.* Engineering and assembling functional nanostructures. *Physics*. Transfer of energy. *Chemistry*. Electrochemistry; photochemistry. *Biology*. Photosynthesis. *Interdisciplinary*. Energy sources and needs and how they can be addressed with new technology; alternative sources of energy.	Chemical reactions; conservation of energy; plant cells/ photosynthesis.
Clean Fuel. Cars of the future may use nonpolluting hydrogen fuel cells. Today, hydrogen fuel is expensive to make, but with catalysts made from nanoclusters, it may be possible to generate hydrogen from water by photocatalytic reactions.	*Nanoscience*. Surface dominance of reactions. *Physics*. Energy changes. *Chemistry*. Thermodynamics; kinetics (catalysts). *Biology*. Enzymes; cellular respiration. *Interdisciplinary*. Clean, cost-effective fuels; fuel efficiency.	Chemical reactions—catalysts/enzymes; conservation of energy; abilities of technological design.

Activity Examples

In the following, we elaborate two sample activities from Table 1.

Tools of the Nanosciences. Leaps in technology and understanding often correlate with leaps in the development of new tools. Nanoscience is progressing at this time, in part, because tools to see, measure, and manipulate matter at the nanoscale now exist. Some of the first technologies that launched this revolution were scanning probe instruments, such as the atomic force microscope (AFM) and the magnetic force microscope (MFM). The same general principle underlies these tools: force between a surface and a cantilever tip causes the tip to be deflected upward and downward, which shifts the position of a laser beam that reflects off the top of the cantilever; the movement of the beam is tracked and used to calculate the cantilever deflection, and (by inference) map the surface of a material. Tools such as these are now used routinely to study molecular and atomic surfaces. However, most students consider a microscope a biology instrument, used to magnify small entities such as cell structures and tissue surfaces; students are not aware that (or how) scientists can see atoms. With the help of Dr. Maureen Scharberg at San Jose State University, we will offer students a way to experience how such tools work and to understand how scientists use these tools to view atomic and nanoscale phenomena. A performance-based ChemSense assessment in which students animate the operation of scanning probe instruments will also be offered as a way to test their understanding.

During the summer of 2003, a student of Dr. Scharberg's designed a large-scale wood model of an AFM (see Figure 2) with support from a San Jose State University (SJSU)/IBM-Almaden Research Center NSF GOALI grant. The cost for the materials for this model is approximately $30. The wood cantilever has a sewing needle tip, and on top of the cantilever near the tip is a mirror. A laser pointer is positioned to beam light from above the cantilever. As the tip skims along a surface, such as copper pellets, a piece of textured plastic, or popcorn kernels, the laser beam reflects the surface onto a piece of paper. From behind the piece of paper, which is attached to a piece of transparent plastic, students can easily trace the amplified surface. Dr. Scharberg and her students have also created a magnetic force microscope model by placing a strong magnet above a nail tip. A refrigerator magnet is then scanned underneath this tip, which results in the tip's oscillating up and down, producing a wave-like pattern that enables students to observe the changes in the magnetic strength.

These AFM and MFM models can help students understand how instruments used in nanotechnology allow scientists to study surfaces at the molecular and atomic levels, and introduce students to a new type of microscope used in science investigations. Under the proposed work, we will collaborate with Dr. Scharberg to refine the protocols for using the models, develop detailed instructions for teachers and students to assemble the models in their classrooms, and create associated curriculum activities and ChemSense tasks to assess their understanding. Assembled versions of these models will become part of a kit, which will also include a real, mobile AFM (purchased by SJSU from Nanoscience, Inc., Phoenix, AZ), which will be available on loan to schools.

Using these models, high school students could examine a range of uniformly or randomly distributed surfaces composed of pure or mixed materials. Students could compare traces from the different instruments and, given unidentified traces made by other students, try to infer the surface type. These activities could lead to discussions of measurement error, identification of impurities in samples, and the advantages and appropriateness of different imaging techniques for different surface types. These activities would provide a revealing view of the instruments and principles behind them.

As an assessment activity, students could be asked to depict the functionality of one of the tools as an animation in ChemSense. The ChemSense animation tool is often used by students and teachers to depict chemical reactions at the nanoscopic level, but it is not restricted to this use. For example, using the animation tool, students could draw the components of the AFM and create an animation that predicts what will happen as the cantilever scans across a surface of a sample. In tandem, they could be asked to draw an associated graph that illustrates the changes in force over the surface as the tip moves in their animation. Students would describe the output of the instrument terms of magnetic repulsion or energy distribution.

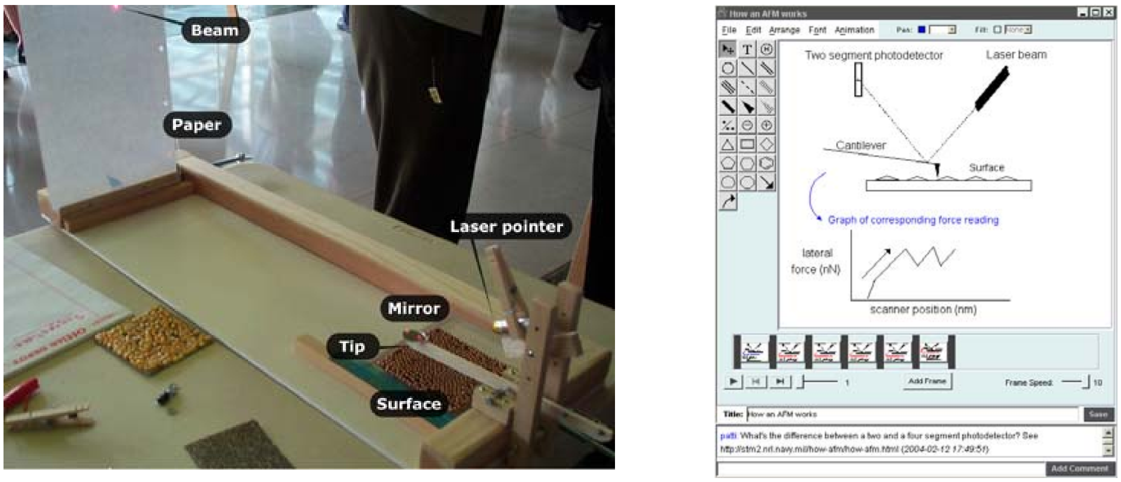

Figure 2. Wood AFM model and screen shot of a possible ChemSense assessment activity.

Carbon Nanotubes. Nanomaterials engineering can result in new materials that exhibit striking physical and electrical properties. For example, before 1980, scientists had identified only a few forms of carbon (diamond, graphite, and amorphous). New forms of carbon have since been discovered, including buckminsterfullerene (“buckyball”)—a soccer-ball-shaped molecule of 60 carbon atoms (C_{60}), and nanotubes—hexagonal fused rings of carbon atoms resembling chicken wire rolled into a tube shape. Nanotubes are single- or multiple-walled tubes with various diameters, lengths, and lattice arrangements. They generally have a large length (several micrometers) and small diameter (a few nanometers), giving rise to a phenomenally large length-to-diameter ratio of about 1,000. Nanotubes have very interesting physical, optical, and thermal properties. They are much stronger than steel and can act as excellent conductors or semiconductors, depending on the proportion of the tube and what (if any) other materials are introduced. Adding nanotubes to other materials, even in tiny amounts (e.g., 1-2%) can greatly enhance physical properties (e.g., strength, stiffness) and electrical conductivity of the material.

Nanoscientists are also designing nanogears out of nanotubes by, for example, attaching benzyne gear teeth. Aligning the teeth is a delicate matter: too close, and the short-range repulsive van der Waals interactions cause the gear to freeze; too far apart, the gear teeth slip past each other. Also, the dynamic motions at this scale lead to vibrations that cause slippage. Lubricants can’t be used, because the lubricant molecules are as big as the gears! The forces and mechanical engineering for gears this size have to be modeled by using new principles.

Nanotubes might also someday be used as “quantum sieves” to separate molecules. For example, hydrogen and tritium (an isotope of hydrogen that has two more neutrons) can fit into a nanotube, but because of vibration (in accordance with the Heisenberg uncertainty principle), the lighter hydrogen can "wiggle out" while the heavier tritium is trapped. Hence, if nanotubes are exposed to a mixture of hydrogen and tritium gas, they should absorb more of the tritium.

Students could use ChemSense to interact with (rotate, zoom) interactive 3-D representations of fullerenes and nanogears to better understand how their structures influence their properties (see Figure 3). They could model the use of nanotubes for filtering hydrogen in ChemSense by drawing and animating hydrogen and tritium gas, introducing nanotubes, and showing how the tritium becomes trapped over time (Figure 3). To investigate electrical properties, students could create nanotube representations on a ChemSense canvas and use the random-motion feature to put their nanotubes in motion and explore the frequency with which they touch to effectively create long, conductive "wires." They could repeat this activity using fine carbon or graphite particles, which are also conductive and used commercially to enhance conductivity of plastics. Although a simplified model, it could highlight how nanotubes are more efficient conductors when added to a material, compared with fine carbon or graphite particles. These activities would emphasize how different molecular arrangements of carbon atoms enhance different characteristics, how carbon-based organic structures vary in their chemical and physical properties, and potential scientific and commercial applications of nanotubes.

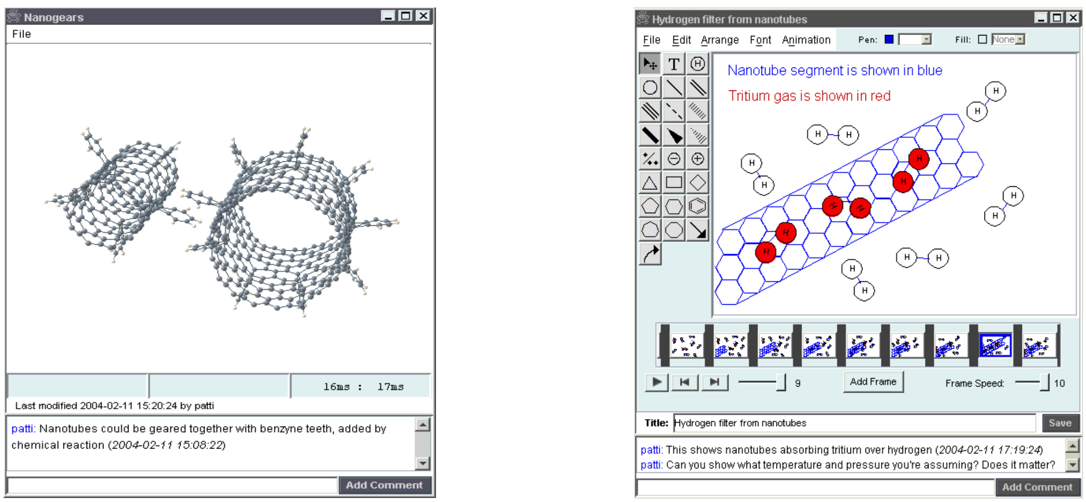

Figure 3. Interactive 3-D model of nanotube gears, and a nanotube hydrogen filter animation.

Tool Expansion

The ChemSense Studio application includes tools to create, share, view, annotate, and edit a variety of representations, including text, images, graphs, drawings, and storyboard animations of nanoscopic processes. We recently added an interactive 3-D molecule viewer to ChemSense, a feature that is particularly important for the study of nanoscale phenomena because the aggregation of molecules in three dimensions determines properties of nanoscale materials. ChemSense also provides a Web interface, called the ChemSense Web Gallery, for viewing and commenting on items. We anticipate some limited extensions to our software, mainly in Year 1, to support our nanoscience activities and to allow for faster and more realistic generation of nanoscale representations. These extensions can be grouped into two broad categories:

Molecular templates. Templates for various molecular aggregates (e.g., carbon nanotubes, liquid water) will be added to the drawing palette to allow for faster and more realistic student generation of nanoscale representations in conjunction with specific ChemSense activities.

Simulation tool. We will integrate an off-the-shelf tool to support the computational simulation of nanoscience processes such as self-assembly. For this purpose, we are considering

Molecular Workbench (http://workbench.concord.org/), a powerful 2-D molecular dynamics modeling engine that simulates the motion of objects based on the fundamental physical interactions between atoms and has a few associated nanoscience activities.

Assessment

Formative and summative tools for assessing student learning of nanoscale concepts will be developed in alignment with the principled assessment approach advocated by Haertel and Mislevy (2003). By design, the ChemSense Studio provides a ready means of formative assessment, since student thinking is made "visible" in ChemSense through the creation of representations. In our prior research with ChemSense, teachers felt they could better assess their students' understanding and provide useful feedback by viewing students' visual representations of chemical phenomena on the computer screen. For the proposed work, we will create a task-specific framework for each activity that the teacher can apply to student work products for both formative and summative assessment purposes. These rubrics will be refined by using student work products to aid teachers in pinpointing essential features that highlight student understanding and application of nanoscience concepts. Additionally, the ChemSense Gallery allows teachers to view and comment on student work (animations, drawings, text, graphs), manage student accounts and groups, and view descriptive data (number of items created and their type, number of comments made, number of logins and most recent login, etc.) on their students and groups via a Web browser. This tool supports immediate, formative assessment, allowing teachers to make timely modifications to lesson plans.

Professional Development

Teachers who wish to adopt or adapt our activities will need to understand the key ideas and concepts inherent in nanoscale science and engineering. Significant teacher learning and mastery of new concepts are more likely to occur through professional development that emphasizes content, multiple materials and scaffolds, active learning, coherence with standards and assessment, and collective participation of teachers (Porter, Garet, Desimone, Yoon, & Birman, 2000; Loucks-Horsley, Hewson, Love, & Stiles, 1998). Our work will blend the characteristics of effective professional development into a program that is based on the following features.

Content focus. Our work with teachers will begin with core concepts important in nanoscience education. We will develop modeling and visualization activities that will help teachers and students acquire competency more quickly and deeply.

Multiple supports. Materials will include professional development materials, classroom activities and instructional materials, assessments, and a guide that walks a teacher through examples of how ChemSense can be used to support understanding of nanoscience concepts. Technical assistance will also be provided throughout the project.

Active learning. Our teachers will advise us as we design activities with our interdisciplinary team of chemists, physicists, educators, and researchers. They will also pilot-test and implement the new activities, review and score student work, reflect on their experience through journals, and be offered individual feedback on their experiences and practices.

Coherence with standards and assessment. All activities developed will be aligned with national (NSES) content standards and will include embedded assessments and rubrics for scoring student work.

Collective participation of teachers. The program will be grounded in face-to-face workshops and regular meetings, with mentoring, peer support, and online involvement via Tapped In, an online teacher professional development community (Schlager, Fusco, & Schank, 2002; see also Results of Prior NSF Support below). We will create a nanoscience education room in the ChemSense building in Tapped In to house resources and support real-time and asynchronous discussion between team members.

Implementation Plan

The success of efforts to develop a suite of instructional materials that can be introduced into the high school curriculum depends on both careful design of these materials and careful classroom testing and evaluation of the materials with diverse student populations. The encouraging results that we report in Michalchik et al. (2003) were obtained with a highly ethnically diverse, lower-middle-class student population at San Leandro High School in California. In our prior ChemSense work, we have been iteratively testing and revising our material with multiple teachers and classrooms from the beginning, through small, initial design studies through more formal, structured studies. In this spirit, our proposed implementation plan will follow a phased approach and will include a wide range of low- to high-performing students. As in our prior work, our budget includes compensation for participating teachers in all phases.

Develop and pilot-test with core teachers. Our team will develop four or five activities per year in the first 3 years and work with a core set of five teachers to pilot-test and refine them based on student and teacher feedback. Each unit will be pilot-tested in at least two classrooms for early feedback on its usability and value. Since our teachers span the traditional high school disciplines (chemistry, biology, physics) and some activities will be more appropriate for particular disciplines, we will stagger development so that teachers in any particular domain area aren't overwhelmed with pilot testing in any particular year. On average, we expect each core teacher to pilot-test two units per year. In this phase, our external evaluator will interview and observe classroom use and provide feedback to SRI staff to help us refine the activities.

Test refined units with multiple teachers. After a unit has been pilot-tested and refined to the point where both our team and our external evaluators consider it ready for wider use, we will try the unit with additional teachers. We will recruit approximately five additional local teachers for this phase of testing. In particular, each refined unit will be tested with at least one core teacher who used it during the unit's pilot phase and with at least two newly recruited teachers. At the first NanoSIG nanoEducation & Training Forum (http://nanosig.org/nanoeducation.htm), held at SRI in November 2003, more than a dozen high school teachers attended and expressed interest in integrating nanoscience activities in their classrooms. We are in contact with these teachers and will recruit teachers from this pool, as well as from local high schools. In our recruiting, we will make it a priority to include a culturally, racially, and socioeconomically diverse set of students and to include teachers from different science subject area backgrounds and different lengths of teaching experience (novice and veteran teachers). In this phase, our external evaluator will conduct another round of more formal classroom observations, interviews, and surveys of teachers using the materials. We will strive to keep the original cadre of teachers constant for assessment purposes, recruit additional teachers in this phase, and stagger testing in a way that minimizes the burden on any particular teacher in any particular school year.

Distribute units widely. The final phase will focus on wide dissemination by training larger groups of teachers to use the materials in a broad set of classrooms. Our main mechanism for dissemination will be six to eight workshops conducted with teachers at national conferences and at San Jose State University, where teacher training facilities will be available to us through our partnership with SJSU. Dr. Scharberg also has extensive experience conducting teacher training workshops. Work in this phase will begin with one or two workshops in the fourth year; the remaining workshops will follow in the final year. In this phase, our external evaluator will prepare and analyze data from workshop surveys administered at the end of each session and, in the final year, conduct follow-up impact surveys with participants involved in workshops the prior year.

Dissemination

Professional articles and presentations. SRI and our partners will present our work in scholarly journals and at various national professional meetings, such as the California Association of Chemistry Teachers (CACT), the National Science Teachers Association (NSTA), the American Chemical Society (ACS), the National Association for Research in Science Teaching (NARST), and the National Educational Computing Conference (NECC).

Teacher workshops. Many professional conferences (e.g., NECC, NSTA) offer full-, half-, and 2-day workshops to teachers to gain new knowledge and explore topics in more depth. In the final 2 years of the project, we will conduct six to eight teacher workshops with scores of teachers at such conferences and at training facilities at San Jose State University.

Material distribution. Our software and activities will be distributed on CD-ROM at national conferences and workshops and will be available for download on our Web site. We are also exploring distribution of our materials in conjunction with a high school chemistry textbook by Brian Coppola (co-Principal Investigator of ChemSense) and colleagues (Coppola, Krajcik, & Kiste, in preparation).

Research partnerships. We will work with the Stanford Center for Probing the Nanoscale (CPN), a proposed NSF Science and Technology Center, and are discussing collaborations with several other groups—including the University of Michigan, Texas A&M University, San Diego State University, Southern University of Baton Rouge, Virginia Polytechnic Institute, and Miami University Middletown—to use our activities in their teacher workshops. Like San Jose State University, CPN will provide nanoprobe kits (real scanning probe instruments on loan, and/or models at low-cost) to schools; our other research partners could also emulate this practice.

Tapped In. To reach and support more teachers cost-effectively, we will present and publish our software and activities in Tapped In, a well-established community of more than 10,000 K-12 teachers, faculty, graduate students, and education researchers engaged in professional development and education reform. Through Tapped In, educators can extend their professional growth beyond courses or workshops with the online tools, resources, colleagues, and support they need to implement effective, student-centered classroom learning activities. We will host several After School Online activities (advertised to Tapped In members via monthly e-mails and a public calendar of events) and provide continuing support to teacher workshop participants through this venue. See Results of Prior NSF Support below for more information on Tapped In.

Project Evaluation

We have allocated approximately 10% of the budget to a third-party evaluator, the Center for Children and Technology (CCT) at Education Development Center, Inc. (EDC). For more than two decades, CCT has been conducting basic, applied, and formative research to investigate how technology can make a difference in children's classrooms, schools, and communities. EDC will act as a critical partner, helping our team shape our strategies for developing our materials and analyzing their usefulness in real classrooms with our teacher partners.

The evaluation process will mirror the three implementation phases of piloting, testing, and disseminating the activities. During each phase, EDC will use a multimethod approach to collect and analyze indicators of the usefulness and value of the curriculum units. EDC's efforts will be both formative and summative, providing ongoing and iterative feedback to the developers in order to appropriately shape the development effort and describing, by the end of the 5-year development period, the degree to which the developers met their goals.

Key evaluation questions in the pilot phase will be formative in nature and focus on how teachers react to the units, how SRI can change the units to make them more useful to teachers, and what types of constructive feedback need to be collected to make improvements. In the testing phase, more summative questions will focus on the measurable learning outcomes resulting from the use of the materials; the feasibility of integrating our materials into the existing contexts and science curriculum, including issues related to teacher understanding and adoption; and student motivation and persistence in studying science. In the dissemination phase, efforts will focus on the receptivity of a wider range of workshop teachers to the activities.

Data collection will include classroom observations, interviews with both teachers and students, and, in the later years, surveys of all teachers who have been trained to use or have used the curriculum. Student outcome data from assessments developed by SRI in conjunction with the curriculum units will be incorporated into this evaluation of both implementation variables and learning outcomes.

Work Plan

This project requires effective coordination between the SRI team and our partner chemists, educators, nanoscientists, and evaluators. SRI will hold one all-day, face-to-face meeting each of the first 4 years at SRI. Additional working meetings and workshops with local teachers and nanoscientists will be held during the year. Throughout the project, our advisory board will provide feedback on the quality, relevance, and application of our work. The tasks to be performed in each year are summarized below.

Task	Y1	Y2	Y3	Y4	Y5
Hold annual advisory board meetings.	•	•	•	•	
Design and pilot test 4-5 activities per year in classrooms of 5 core teachers.	■	■	■		
Expand software tools to support the activities.	■	■			
(EDC) Conduct formative evaluation of piloted activities and tools.	■	■	■		
Analyze pilot results and revise materials and tools based on classroom findings.		■	■		
Recruit 5 new, local teachers for second phase of testing refined materials.		■			
Conduct classroom testing of refined materials with 5 core and 5 new teachers.			■	■	
(EDC) Conduct summative evaluation of use and impact of tested materials.			■	■	
Analyze student learning, teacher practice, and classroom implementation data.			■	■	
Submit conference workshop proposals, recruit teachers for SJSU workshops.			■	■	
Conduct training workshops with teachers at national conferences and SJSU.				■	■
Disseminate results through conferences, journals, online forums (Tapped In).			■	■	■
Disseminate activities and software through project Web site and CD-ROM.				■	■
(EDC) Conduct summative evaluation of workshop impact.					■

Personnel

Dr. Patricia Schank will serve as the project's Principal Investigator, providing overall leadership and coordination. Dr. Schank is a senior research scientist at SRI's Center for Technology in Learning and Principal Investigator for the ChemSense project. Her research focuses on the design and development of computer-based tools to support science learning. She is the chief designer of the Tapped In and PALS systems (see Results of Prior NSF Support) and technology director for PADI, a theory-based approach to developing quality assessments of science inquiry. **Dr. Anders Rosenquist** will co-direct the project, overseeing the design of our nanoscience activities and assessments. A research scientist at SRI and former high school physics and chemistry teacher, Dr. Rosenquist has held design and development roles on a range of technology-supported projects, leading the development of probeware-based chemistry modules and PALS performance-based assessments. **Dr. Vera Michalchik**, an educational researcher at SRI trained in both anthropology and cognitive science, will lead the classroom implementation and evaluation activities. **Ms. Tina Stanford**, an educational researcher at SRI, veteran chemistry and biology high school teacher, science teacher trainer, and assessment developer and coordinator, will lead the activity and assessment development work.

Additional domain expertise in chemistry will be provided by **Dr. Nora Sabelli**, co-director of the Center for Technology in Learning at SRI and former chemistry professor; by **Dr. Brian Coppola**, professor of chemistry at the University of Michigan and coauthor of a new high school chemistry textbook; and by **Dr. Maureen Scharberg**, professor and director of science education in the chemistry department at San Jose State University. Dr. Scharberg will also lead the development of three to six modules, consult with the project on remaining modules, and provide expertise in curriculum design and teacher training. SRI nanoscientists **Dr. Yigal Blum**, **Dr. Marcy Berding**, and **Markus Krummenacker** will consult with the project to provide additional domain expertise in the areas of nanotechnology, physics, and biology, respectively.

Five high school teachers—**Nancy Day** (science teacher, Menlo-Atherton High School, Menlo Park, CA), **Irene Hahn** (chemistry teacher, Miramonte High School, Orinda, CA), **Carolina Sylvestri** (chemistry and physics teacher, Gunn High School, Palo Alto, CA), **Geri Horsma** (biology teacher, Gunn High School), and **Doris Mourad** (chemistry teacher, Castilleja School, Palo Alto, CA)—have enthusiastically agreed to work with the NanoSense team to advise the development of our activities, pilot-test them in their classrooms, and provide feedback on their use (see letters of support). These schools represent a range of low- to high-performing students from culturally diverse populations. **Menlo-Atherton**'s student population is approximately 40% Hispanic, 9% African-American, 4% Asian, and 5% Pacific Islander; 23% of the students' parents hold a college degree and 32% attended graduate school; and 16% of the student body qualify for free or reduced-price lunches. The school's 2002 API score was 696 out of 1,000. **Miramonte**'s student population is 16% Asian, 3% Hispanic, and 1% African-American; 35% of the students' parents hold a college degree and 57% attended graduate school; and fewer than 1% of the student body qualify for free or reduced-price lunches. The school's 2002 API score was 871 out of 1,000. **Gunn**'s student population is 26% Asian, 5% Hispanic, and 2% African-American; 16% of the students' parents hold a college degree and 75% attended graduate school; and 4% of the student body qualify for free or reduced-price lunches. The school's 2002 API score was 883 out of 1,000. **Castilleja** is a nonsectarian, all-female private school; approximately one third of the student population are ethnic minorities, and virtually all graduates go on to four-year colleges.

Education Development Center, Inc. (EDC) will conduct the external evaluation of the project under the direction of **Dr. Ellen Mandinach**, associate director for research at EDC's Center for Children and Technology. Dr. Mandinach has a strong background in research methodology and measurement and has done extensive work in the field of educational technology. She will travel to the Bay Area at least twice a year to visit schools using NanoSense, and between trips will be aided by **Scott Graves**, an independent consultant who lives in the Bay Area and will help EDC with data collection at school sites and workshops.

An advisory board has been established to monitor and guide the quality, relevance, and application of our work (see letters of support). **Dr. Robert Tinker** is a physicist who serves as president of the Concord Consortium and directs the Molecular Workbench project. **Dr. Larry Dubois** is a nanoscientist and vice president of the Physical Sciences Division at SRI. **Deb Newberry** is a former nuclear physicist, current nanoscience technology instructor at Dakota County Technical College Nanoscience Technology Program, and coauthor of the popular nanotechnology book *The Next Big Thing Is Really Small*. **Christine Peterson** is cofounder (with Eric Drexler) and president of Foresight Institute, a nonprofit that educates the public, technical community, and policy-makers on nanotechnology and its long-term effects. **Dr. Michael Ranney**, professor of education at the University of California, Berkeley, specializes in the study of reasoning, development of curricula to support critical thinking, and the integration of scientific, mathematical, engineering, educational, and societal understandings. **Dr. Maria Kozhevnikov**, a cognitive scientist at Rutgers University, is an expert on visual-spatial learning and how individual differences affect more complex activities, such as physics learning.

Results of Prior NSF Support

ChemSense (REC-0125726, $1,158,750, 1/02-12/04; REC-9814653, $1,212,228, 1/99-12/01). The ChemSense project (http://chemsense.org) is analyzing the effects of sustained integration of the ChemSense curriculum and visualization tools in high-school- and university-level chemistry courses. The ChemSense Studio software helps students visualize and construct nanoscopic entities and processes. Students view and comment on one another's expressive contributions through the software to collectively arrive at new understandings. Teachers gain new insights into student understanding by assessing students' stepwise animations and explanations. Our research documents student and teacher learning, changes in representational and discursive practices, and challenges and benefits of integrating representations into classroom practice.

Adapting High-End Visualizations to a Student-Centered Learning Environment. Under two NSF subawards, SRI developed a molecule viewer and editor in ChemSense to render interactive 3-D molecule representations (ACI-9719019 No. 807, $80,000, 2/99-9/03) and conducted a summative evaluation of the ChemViz II visualization tools and materials, used in several high schools (ESI-9819106 No. 01-315, $80,520, 2001-2002).

Tapped In (REC-9725528; $1,414,336, 12/97-11/00; REC-0106926, $249,983, 7/01–1/03). Tapped In (http://tappedin.org) is an online community for professional development providers and educators, created by SRI to transform teacher professional development. Tapped In enables providers to offer high-quality online professional development experiences and support to more teachers cost-effectively. Through Tapped In, organizations can develop, implement, and manage online courses, workshops, seminars, mentoring programs, and other collaborative activities that supplement, or function in lieu of, face-to-face activities. Tapped In experts work with organization staff to design and facilitate online activities that are motivating, standards based, and attuned to the learning styles and technical facility of participating teachers.

Performance Assessment Links in Science (PALS) (ESI-9730651, $1,496,441, 1/98-12/02). PALS (http://pals.sri.com) is an online, standards-based resource bank of more than 300 science performance assessment tasks indexed via the National Science Education Standards (NSES) and various other standards frameworks. The tasks, collected from numerous sources, include student directions and response forms, administration procedures, scoring rubrics, examples of student work, and technical quality data calculated from field testing.