Learning at the nanoscale: Research questions that the rapidly evolving interdisciplinarity of science poses for the learning sciences

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Abstract: Recent interdisciplinary discoveries in the sciences and engineering at the nanoscale, specifically in our ability to manipulate, molecules at atomic scales, suggests a need for the education community to reconsider the ways in which disciplinary-based sciences and mathematics are being taught in schools, as well as how the public might engage with nanoscale phenomena. This session will discuss key learning questions and their importance in helping to advance both conceptual reasoning from the macro, micro, nano, and atomic levels, as well as their implications for curricular restructuring, public programming, and teacher professional development. The timeliness and broader importance of this research derives in part from two NSF-sponsored workshops on nanoscale education held in 2005, the National Nanotechnology Initiative, and two multi-institutional NSF awards: a National Center for Learning and Teaching and the Nanoscale Informal Science Education Network. This session will discuss research implications for the learning sciences and education community.

Background

The U.S. federal government has placed nanoscience and nanotechnology as one of its top R & D priorities because of its potential to revolutionize medicine, computing, materials science, energy production, and manufacturing. This investment has created the National Nanotechnology Initiative (NNI; NSTC/NSET, 2005) and the National Nanotechnology Infrastructure Network to support the development of research, programs, and tools to advance nanoscience and nanotechnology research and education (Roco and Bainbridge, 2002; Roco 2003) The impact of nanotechnology on manufacturing processes and everyday applications makes this investment important for education, and calls for cognitive and pedagogical research around issues of scale which run across all scientific disciplines.

To make these advances visible and comprehensible to all audiences, the National Science Foundation has made two substantial awards. One award targets public audiences through the establishment of a national infrastructure that links science museums and other informal science education organizations with nanoscale science and engineering research organizations, called the National Nanoscale Informal Science Education (NISE)[1] Network led by the Museum of Science Boston along with the Exploratorium and the Science Museum of Minnesota. NISE's goal is to foster public awareness, engagement, and understanding of nanoscale science, engineering, and technology. The second award, the Nanoscale Center for Learning and Teaching (NCLT)[2], with Northwestern University, Purdue, the University of Michigan, and a large number of institutional partners, is aimed at the college and pre-college science education communities.

In addition, two NSF-sponsored workshops were held recently to consider aspects of nanoscale education: one at SRI's Center for Technology and Learning (CTL) and other at the National Science Foundation. The CTL workshop at SRI International brought together a wide variety of participants including educational researchers and science educators (spanning high school, community college, and university levels), nanoscientists, science museum and informal learning specialists, and workforce development staff to consider the integration of concepts of the nanoscale with science education. In particular, the workshop identified core nanoscale concepts and discussed their representations, and considered needs and directions for research related to nanoscale education (Sabelli et al., 2005).

The primary goal of the NSF workshop was to bring together principal investigators of awards funded by the NSF Division of Elementary, Secondary, and Informal Education and the education coordinators of several nanoscience research centers, to facilitate both knowledge transfer among participants, and moves towards defining a coherent nanoscience education vision.

Introduction – A Climate for NSET Education

This ICLS session will explore the need for learning scientists to consider educational implications of the initiatives in nanoscale science, engineering, and technology (NSET). Researchers concurrently and collaboratively working on middle school science curricula, interactive modeling software, teacher professional development, exhibitions in museums, and public understanding of nanotechnology will share the multiple approaches and challenges in which learning at the nanoscale is being facilitated, implemented, and assessed across settings and audiences.

The nanoscale is unfamiliar to students and relatively inaccessible. Compared to everyday experience, different forces are important, friction is almost never encountered, everything is in thermal motion, and odd quantum effects are observed. To develop an understanding of this world, the learner needs to depend on indirect evidence, mental models, and computational environments. It could be argued that these concepts are too difficult to tackle until students reach an advanced undergraduate level and can handle sophisticated mathematics. It is, however, desirable for a much broader range of students to gain a general conceptual understanding of the area for various civic and economic reasons and because the complex, interdisciplinary nature of nanotechnology better reflects modern science than the usual disciplinary treatment. Furthermore, the science concepts that are important at nano scale provide deep linkages between disciplines. Taught at a conceptual level, they could make large parts of science more accessible and motivated. It is possible that student exploration of computational models can develop the needed concepts (Tinker, 2005a; 2005b).

A conceptual framework, responsive to the new interdisciplinary, system-oriented ways of doing and using science is needed if a *coherent* curriculum vision can be refined. While views of the curriculum have evolved (AAAS, 1989; AAAS, 2001), the underlying expectations and structure assume the current sequencing, and does not yet reflect the cumulative impact of the changes that have taken place in the field of science, engineering, and technology. Two possible frameworks derived from the technologically-driven methodological advances are catalysts for deep science curricula reform. They are (a) complexity: i.e. the systemic, self-inferential, multi-level nature (Waldron, 1992, Holland, 1998, Kaput et al., 1999) of the scientific issues that confront citizens in making sense of political discussions and reaching personal decisions (global change and risk assessment of genetically engineered foodstuffs for example), and (b) the scientific and technological advances that have enabled the study and manipulation of matter at the nanoscale, where chemistry, physics, biology overlap, and where engineering and design takes a more eminent role. Either complexity (see Sabelli, 2005) or nanotechnology can be used as a lens to analyze ways in which curriculum can addresses the evolution of science in support of science education goals.

In this session we will discuss the educational importance of looking at the nature of matter as a continuum that has been made clear by the practical applications of nanotechnology (see, for example, Roco, 2004). This approach shares a starting point with Lederman's "physics first" curriculum, which uses the interdisciplinary molecular basis of nature as its conceptual underpinning (Lederman, 2001). Our aim is to explore how learning sciences research can use the issues of learning at the nanoscale to help learners to develop a more coherent and integrated understanding of science and its methods, without adding nanoscience to an already impacted curriculum to benefit from the affordances of interdisciplinarity.

Emerging NSET education research question

The two events mentioned in the background section generated preliminary key research questions that need the help of the learning sciences to be addressed. In March 2005, SRI International convened a working meeting to discuss conceptual issues related to *integrating the science and technology of the nanoscale into science education* (Sabelli et al., 2005). In October 2005, NSF convened a workshop on K12 and Informal Nanoscale Science and Engineering Education gathering participants from different science and technology centers and education outreach projects to take stock in the progress so far in nanoscience education and outreach. A key goal of this NSF workshop was to promote synergies between researchers and practitioners working in the formal and informal learning areas, and move towards defining a coherent nanoscience education vision. The two workshops were complementary: nanoscience education and awareness (NSF) and integrating scale in science education (SRI CTL).

In both these meetings, key learning research questions and nanoscience key principles were identified by consensus and agreed upon as important to address. With the participation of the learning sciences community, these questions could be further investigated to convert principles into learning goals and to formalize a research agenda.[3] A workshop to start the process is being planned for early 2006.

The broad set of questions posed during the workshops are as follows:

- What are possible development trajectories for 5 – 12th grade students to learn major learning goals related to nanoscience (or interdisciplinarity and complexity)?
- How do people reason about scale? How do we get learners to understand crossing boundaries from macro, micro, nano, and atomic levels?
- Given that people cannot see nanoscale phenomena with the naked eye, what do learners extract from the various visualizations, representations and models we design for them?
- What is the role of physicality and experiential activities when dealing with nanoscale phenomena?
- What are the scaffolds, models, representations, and/or exhibit interactions that lead to educational progress? And how do they evolve/change with the learner over time?

Cognitive research questions relate to the importance of understanding not only each scale independently, but also the transition between scales of matter: When does an object stop being a collection of individual atoms or molecules and become a "material?" If the components are identical when there is a larger aggregate of particles, forming a bulk amount of the same substance, is it the same "material" or not? Is there a rule that aptly describes the transition area between a nanoscale object and a bulk object? These questions apply in physics as much as in chemistry and in biology. There is not a "nanoscience" as such, rather a science of matter at the nanoscale where the boundaries between disciplines becomes blurred. It is thus educationally exciting to explore how integrating scale into science school subjects can lead to a more coherent conceptual understanding of science. It is where the boundaries between disciplines blur that we can attempt an integrative pedagogy.

In addition to cognitive aspects, there are epistemological considerations about the nature and conception of 'small' and beliefs about what exists when the science phenomenon is invisible to the naked eye. For example, when adults, teens, and children were asked about the smallest thing as objects they could conceive, a majority across all ages said a piece of dirt or a grain of sand. (see Waldron et al., 2005) Can learners really reason mathematically or conceptually at 10^{-9} meter scales? Or does this even matter that this might not be comprehensible or teachable? Research into conceptual bridges of how to teach ideas that small quantitative changes lead to large qualitative differences, and that matter can be studied as individual particles, a group of particles or a large group of particles, might help lower barriers to understanding of why nanotechnology has become so important, and how it forces the interconnections among scientific disciplines. This, in turn, could help learners acquire a more coherent version of science and of scientific advances.

Prior and Related Research and Evaluation on NSET

Prior research has addressed some of these questions in the context of discipline-based classroom teaching such as chemistry or physics (Harrison and Treagust, 1996; DeWos and Verdonk, 1996; Johnstone, 1993) Some of these questions have been addressed by research into advanced learning tools to support visualization and haptic interactions by students to address learning morphologically accurate models of viruses (Jones et al., 2002). Other interventions have demonstrated the success of linking molecular representations with symbolic and macroscopic phenomena using multimedia-based instruction (Ardac and Akaygun, 2004). For example, the Concord Consortium has developed a molecular dynamics (MD) engine for education that uses classical mechanics to predict the motion of particles that act under forces that approximate the forces on atoms and molecules (Pallant and Tinker, 2004; Xie and Tinker, 2005). Using molecular dynamics software, students can interact with and build models of liquid crystals, self-assembly, and protein conformation. [4]

Because the field of nanoscience is still new to many, there are few if little documented prior studies of conceptions or misconceptions about nanotechnology among the public or learners in both the US and in Europe (Cobb and Macoubrie, 2004; Lee, Scheufele, and Lewenstein, in press). This presents an interesting opportunity for NSET learning sciences research and education in formal and informal settings.

In museums and science centers, several formative studies and evaluations have been conducted that studied visitors' ideas about atoms, molecules, and scale before visiting exhibitions; and public audience reactions to exhibitions that focus on nanoscale phenomena, nanoscience and nanotechnology (e.g., *NanoZone, Strange Matter, Marvelous Molecules (*Serrell and Associates, 2001) *It's a NanoWorld, Too Small to See*.)) These studies found that visitors have difficulty reasoning about things they can't see, don't differentiate between micro (10^{-6}) and nano (10^{-9}), and had difficulty ranking an atom, DNA, and cell by size (Stafford and Molinaro, 2005; Holladay, 2005; Waldron et al., Korn et al., 1999). Adults and children alike are challenged by interactions and phenomena at the nanoscale. Social sciences research has also been done on public perceptions of nanotechnology focusing upon people's assessment of potential benefits and risks associated with the field, preferences for learning about applications, and their limited awareness of nanotechnology issues (Flagg, in press). As more public forums, educational media, and new NSET exhibitions are developed, learning scientists have even more opportunities to study learning at the nanoscale with the learners of all ages in the general public, and to contribute research-informed design principles to foster designs for greater engagement with and understanding of nanoscale science, engineering, and technology in a more comprehensible and interdisciplinary way.

Conclusions

Nanoscale research challenges both the learning and science research communities to jointly explore new pedagogies needed and to create approaches to communicate why the work of nanoscale scientists and engineers has attained such visibility and how it might also engage the general public, not only nanotechnology specialists. Changes in observable properties with scale are not cognitively obvious, and the ability to manipulate matter at these small scales is creating a new paradigm in manufacturing. To inform the public about the advances in scientific research, and to capture the imagination of new generations of diverse communities of youth who may choose careers in science and engineering requires research that considers changes in science when these changes have become so fundamental to society. Addressing these challenges will hopefully lead to new thinking, techniques, and partnerships between learning scientists, educators, and scientists, just as the advancement of nanoscale science, engineering, and technology has led to new disciplines, technologies, and collaborations. The learning sciences community has both a body of empirical research and prior knowledge to contribute, as well as expertise to advance research on learning and teaching at the nanoscale. However, without focused collaboration and continued interactions across disciplinary boundaries and without learning scientists taking an active role and voice in these endeavors, another opportunity will be missed to make deep science educational progress.

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[1] NISE URL: http://www.nisenet.org
[2] NCLT URL: http://www.nclt.us/
[3] The latest version of both reports will be available at the ICLS session.
[4] The force used in most Molecular Dynamics simulations from the Concord Consortium is derived from the Lennard-Jones potential. Through the tools, three objects and related forces can be added to the basic MD model that allows the system to illustrate some important nano-science concepts: Gay-Berne particles, Smart Surfaces, and water interactions. Using these, students can interact with and build models of liquid crystals, self assembly, and protein conformation.