The impact of the nanoscale vision on the future of learning and teaching**

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ABSTRACT

The evolution of the field of nanotechnology has propelled humankind to the brink of an impending revolution, which will fundamentally impact every aspect of human life. While theory and experimentation are indeed critical to this future, simulation will play a key role in the shape of this future. To this end, the field of nanotechnology has required significant advances in the way cyberinfrastructure is utilized to derive scientific progress. To sustain and indeed fuel growth in nanotechnology requires a new generation of scientists – currently in middle and high schools and in colleges and universities –trained to think and perform across disciplinary barriers. The task of reaching these students and to capture their imagination requires a fundamental and systematic approach – that is positioned at the convergence point of nanotechnology, pedagogy, and cyberinfrastructure. The Network for Computational Nanotechnology (NCN), through its nanoHUB.org website, is leading a new charge in bridging nanotechnology discovery and learning. In this paper, we will use the nanoHUB.org as a case study to highlight how the nanoscale vision is impacting teaching and learning at various levels.

Keywords: Teaching and learning, nanotechnology, next-generation learning, science gateways, nanoHUB, NCN

1. INTRODUCTION

The evolution of nanoscale science, engineering, and technology as areas of scientific inquiry has brought into sharp relief the critical importance of innovating curricula at all levels. While nanoscale phenomena – both theoretical and practical – themselves offer significant pedagogical impediments, the problems are further shaped by the evolution of simulation as a key methodology for scientific inquiry. Traditional methodologies have relied heavily on theory and experimentation for the purposes of expanding scientific knowledge. However, with the advent of nanotechnology as an integrated area of study, simulations that depend on heavy computational resources have risen in importance as the third leg of the science. Pedagogies currently in use at all levels of the educational system, however, still rely on theory and experiments as the primary methods for teaching and learning science, engineering, and technology. The fundamental debate on the teaching and learning of nanoscale science and technology, however, does not begin with the introduction of simulations in instruction. Nanotechnology has triggered a deeper philosophical debate in the teaching and learning community – namely, “why should we teach nanotechnology at the K-12 levels (start of the pipeline)? What about nanotechnology is so unique that was not seen at the microscale or larger?” Beyond this philosophical debate lies the realm of the actual pedagogical questions themselves. If we want to introduce nanoscale science, engineering, and technology at the start of the pipeline (K – 12) and also at the undergraduate and graduate levels, how do we go about making a systematic curricular transformation? After all, physics and chemistry have been dealing with a number of the nanoscale concepts for a significant time now – what makes the integrated view somehow different? Some direction on how to start answering these questions can be found in an article by Roco (2003) [1] which states that “Nanoscale science and engineering are providing us with unprecedented understanding and control of the matter at the most fundamental level: the atomic and molecular structures that are the foundation of all living systems and man-made products. Indeed, the same principles and phenomena apply at the nanoscale across every discipline, leading to increased coherence in knowledge, education, and technology” (p. 1). This convergence of scientific insights to reshape

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every aspect of how science is understood is extremely new even to the scientific community. Due to a significant gap – which many argue despite best efforts is broadening – between discovery and learning, the integrated view of science has not yet percolated into the educational zeitgeist. Therefore, there is still a severe shortage of pedagogical perspectives into how nanoscale science and engineering will influence the future of teaching and learning. Efforts such as the National Science Foundation (NSF) funded National Center for Learning and Teaching (NCLT) in Nanoscale Science and Engineering and the Network for Informal Science Education (NISE) in Nanoscale Science, Engineering, and Technology have already started to address these issues. The scientific world fueled by industry demands, however, is moving forward at a breakneck speed, which is significantly higher than that of progress in pedagogical theory building.

The purpose of this paper is to examine the role of science gateways such as the NSF-funded Network for Computational Nanotechnology's nanoHUB in blending cutting-edge research and simulation tools into day-to-day classroom curricula. The paper further argues for a new paradigm in teaching and learning that seeks to embed teaching and learning into the daily lifestyles and technology choices of students. It also discusses how nanoHUB is setting new trends in delivering and packaging scientific content to students. Before we can discuss the nanoHUB, it is important to identify and stratify the pedagogical problem that is seen in teaching nanoscale science, engineering, and technology concepts at various levels.

2. PEDAGOGICAL BACKDROP

The purpose of this section is to provide a general pedagogical backdrop for the role that nanoHUB can play in teaching and learning nanoscience and technology. It is not meant to be exhaustive or an in-depth analysis of the trends at each educational level. Teaching nanoscale concepts presents differing challenges at various levels of education. While there is some overlap in the type of pedagogical challenges that are seen across the pipeline starting from K – 12 levels into the graduate levels, there is a clear transition in the type of problems that is seen. At the K – 12 levels the scientific domain of nanotechnology presents a high barrier to entry. The fundamental problems of teaching nanoscale science and technology at this level is well described by Sabelli et al. (2005) [2] as: "The problem is conceptual and practical; objects and concepts at the nanoscale are hard to visualize, difficult to describe, abstract, and their relationships to the observable world can be counterintuitive." Teaching nanoscience and nanotechnology at the start of the pipeline is largely constrained also by the level of development of cognitive abilities of students at this level. Abstract thinking a key ingredient to understanding nanoscale science and technology is still not completely developed in children at the K – 5 levels. Pedagogical approaches are moving towards focusing efforts in teaching nanoscience and nanotechnology at the 7 – 12 levels. Approaches, such as story telling, use of interactive animations using cartoon-like characters, and high quality interactive games have not yet been fully explored to teach nanotechnology at various levels. It must, however, be pointed out that such efforts to use media named above are underway [3, 4]. Furthermore, teaching and learning at the K – 12 levels is strongly constrained by state and federal educational standards. While these standards allow some liberty to introduce new concepts into the classroom curricula, they still place a very tight corset around what learning goals and concepts are important for assessment at that level. The over-emphasis on assessment introduces the real risk of negative washback – that pushes teachers to teach to the test as opposed to teaching the scientific concept of value. There is, however, a growing awareness in the K – 12 educational community about the importance of teaching some nanoscience and nanotechnology concepts at this level. It can be safely assumed that given this increasing awareness of the importance of nanotechnology to people's daily lives, this emphasis on introducing nanoscale concepts at the start of the pipeline – namely K – 12 levels – is only going to increase.

At the undergraduate and graduate levels, teaching nanoscience and nanotechnology is just starting to pick up. Despite significant scientific work in this area, the number of institutions introducing nanoscience and nanotechnology in their core curricula is just starting to grow. There is tremendous room for innovation at the undergraduate and graduate levels also. At the national and international level, there have been significant calls for funneling cutting-edge research results into the undergraduate experience. These calls not withstanding, the gap between work on-going at the very edge of scientific progress remains far away from what is being taught in the classrooms. One of the pedagogical trends that has emerged out of cutting-edge "research to understand, simulate, and design electronic devices comprised of single molecules" [5] is being introduced by the Network for Computational Nanotechnology. This approach is known as the *bottom-up approach to teaching electronic devices*. The rationale is provided as follows: "The promise of nanotechnology will not be realized until we educate engineers differently. Chemistry, for example, is taught from the bottom up by beginning with the simple hydrogen atom, then slowly building up to more complex molecules. Electronic devices, however, have traditionally been taught from the top down, beginning with large devices that contain millions of atoms. When applied to the molecular-scale devices now being explored, this traditional approach is more confusing than illuminating" [see 5 and 6].

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In addition to fostering new approaches to teaching nanoscale science, engineering, and technology, the NSF-funded Network for Computational Nanotechnology (NCN) also maintains a science gateway the provides a single point of aggregation for simulation tools and educational materials. The NCN's science gateway is called the nanoHUB [7], which is rapidly influencing both research and education in its core areas of nanoelectronics, nano-electromechanical systems/nanofluidics, and nanobiology. The remainder of this paper will be dedicated to discussing the nanoHUB's core capabilities and innovations that are fostered through this effort that have started to impact learning. At this point, we must point out that a whole area of informal science education – that involves educating the general public – has not been discussed in this paper as it lies well outside the purview of formal educational efforts that this paper discusses. However, in cases where a discussion or reference to informal science education is needed, we will provide appropriate discussions.

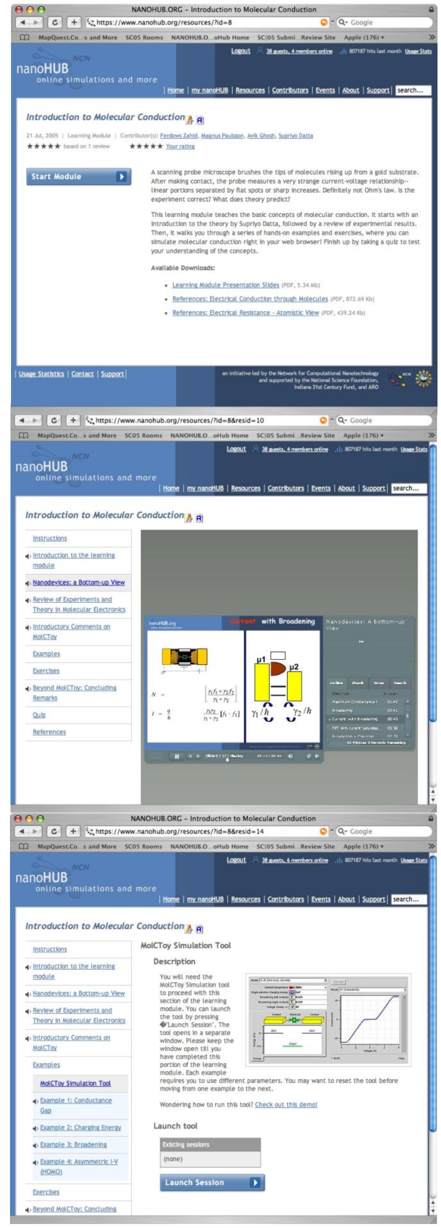

Fig. 1. Sample Learning Module showing abstract, voiced presentation, and simulation tool

3. SCIENCE GATEWAY: BRIDGING DISCOVERY AND LEARNING

As mentioned earlier in the paper, simulations play a critical role in advancement of nanoscale science, engineering, and technology. One of the key elements that allow the development and deployment of high quality simulation tools is the required cyberinfrastructure [see 8 for an elaboration of cyberinfrastructure] to facilitate the aggregation of tools and materials into single point of entry portals called *science gateways*. Goasguen, Madhavan, et al. (2005) [9] define science gateways as "as an integrated ecosystem of infrastructure, middleware, educational and content aggregation tools that will provide the primary means for conducting science in a specific field. Furthermore, ideally the cyber-services offered by the science gateways should be available to the larger community through traditional media such as the web, and also through emerging mobile platforms such as PDAs and cell phones" (p. 1). Critical to the development of science gateways is the access to significant computational resources – such as those available through the NSF-funded TeraGrid [10] or the Open Science Grid (OSG) [11]. The science gateways use middleware technology – usually developed generically to be discipline agnostic – to provide the link between the user interface and the computational resources. The idea behind science gateways is to allow users to focus on the science, rather than on the underlying infrastructure. The nanoHUB hosts a variety of simulation tools that range from simple toy tools to advanced simulation tools that can submit jobs to large clusters and can run for several days. The area of nanoHUB that is most relevant to this paper is the methodology that is being used to embed scientific grade simulation tools along with learning materials using a methodology called learning modules. The next section elaborates on this new and innovative concept called learning modules.

3.1. Learning Modules: Contextualizing education through standard compliance

Over the last year, the NCN has made significant progress in not only solidifying an aggressive education and educational technology vision, but also in ushering in a new paradigm in how discovery and learning can be bridged. The NCN's key educational strategy is to contextualize learning by encapsulating the signature service - namely, online simulation – with lectures, seminars, examples, and exercises into a single educational unit. In 2005, NCN demonstrated the use of learning modules on the nanoHUB - a new methodology for aggregating content and presenting it to users in pedagogically sound ways. Over the past year, the nanoHUB team has increased the total number of learning modules available to users from 1 (in 2005) to 9 (currently). This paradigm has informed every scientific theme within the NCN and the theme leaders are planning on significantly increasing the number of full-fledged modules they develop and deliver through the nanoHUB. Additionally, the notion of learning modules to contextualize research within learning is starting to attract industrial partners to the NCN as it holds a lot of potential for standardizing the way content is delivered across the globe.

One of the biggest challenges in modern day pedagogy is to facilitate a firm understanding of scientific concepts through hands-on exercises, while simultaneously preparing students for the cutting-edge research and work environments in the real world. Modern trends in pedagogy - such as inquiry-based learning, problem-based learning, impact of scaffoldings, and zone of proximal development [12, 13, 14, 15] – therefore, demand that students be provided authentic learning experiences. The new nanoHUB content aggregation strategy of pre-assembling a variety of content assets in appropriate contexts is highly consistent with this pedagogical demand. By combining advanced simulation tools available within the nanoHUB together with seminars, lectures, assignments, and quizzes, the nanoHUB furthers the NCN learning mission significantly. Furthermore, learning modules are compliant with global e-learning specifications and leverage extensively on NCN research initiatives.

In order to facilitate the widespread diffusion of nanoHUB content not only into the classroom curriculum, but also to serve as a national model of the innovative link between discovery and learning, we continue to stabilize (and make enhancements to) this new content packaging strategy using Shareable Content Object Reference Model (SCORM v1.2) [16] as the underlying metadata format. Please note that SCORM itself is an implementation of the IMS Content Packaging and Sequencing Specification. For a detailed discussion of IMS and SCORM please refer to [17], [18], and [19]. The use of SCORM has not only immediately rendered all nanoHUB content compliant with global e-learning practices; it also enabled a simpler and streamlined content creation strategy. The adoption of SCORM has transformed even simple content like nanoHUB seminars and presentations into digital content known as "learning objects". While underlyingly every online presentation that uses the Breeze technology is a learning object, for the sake of clarity, we use the term learning objects only for larger self-contained units that include multiple lectures seminars, papers, and simulation tools. Currently over 200 online presentations that use the Macromedia Breeze technology are inherently learning modules that are compliant with global e-learning specifications. Learning objects are by definition interoperable with most standard course management systems and include clearly stated instructional goals along with necessary assessment.

The last decade has seen the widespread adoption of course management systems (CMS) on university campuses. According to Green (2003) [20], " [...] a third (33.6 percent) of all college courses now use course management tools, up from 26.5 percent in 2002, 20.6 percent in 2001, and almost double the level in 2000 (14.7 percent)." He elaborates further that the course management system (CMS) is now "a core component of the institutional instructional infrastructure." In the CMS world, "interoperability" and "reusability" have become key requirements. Global e-learning specifications such as IMS and SCORM are grounded on these values. Clearly, it is in this context that the ability of nanoHUB content to interoperate with various CMSs will be critical.

3.2. Assessment through service-oriented Sakai Integration

The NCN educational vision states that the nanoHUB will have *systemic impact*. Therefore, it is extremely critical for the NCN team to set an overall agenda for the measurement of research and educational impact. Over the past year, over 1200 unique users have used learning modules described above. This increase in the total number of users is an indication that nanoHUB is starting to gain a critical level of acceptance among the research and educational communities as an educational tool. Measurement of impact based on just the total number of users, however, is an inadequate measure of nanoHUB impact. Any serious educational effort has to measure more than the quantity of the educational materials being used, but also determine if the use of these materials and associated media formats produce serious learning gains. The assessment of online learning still presents several open research questions.

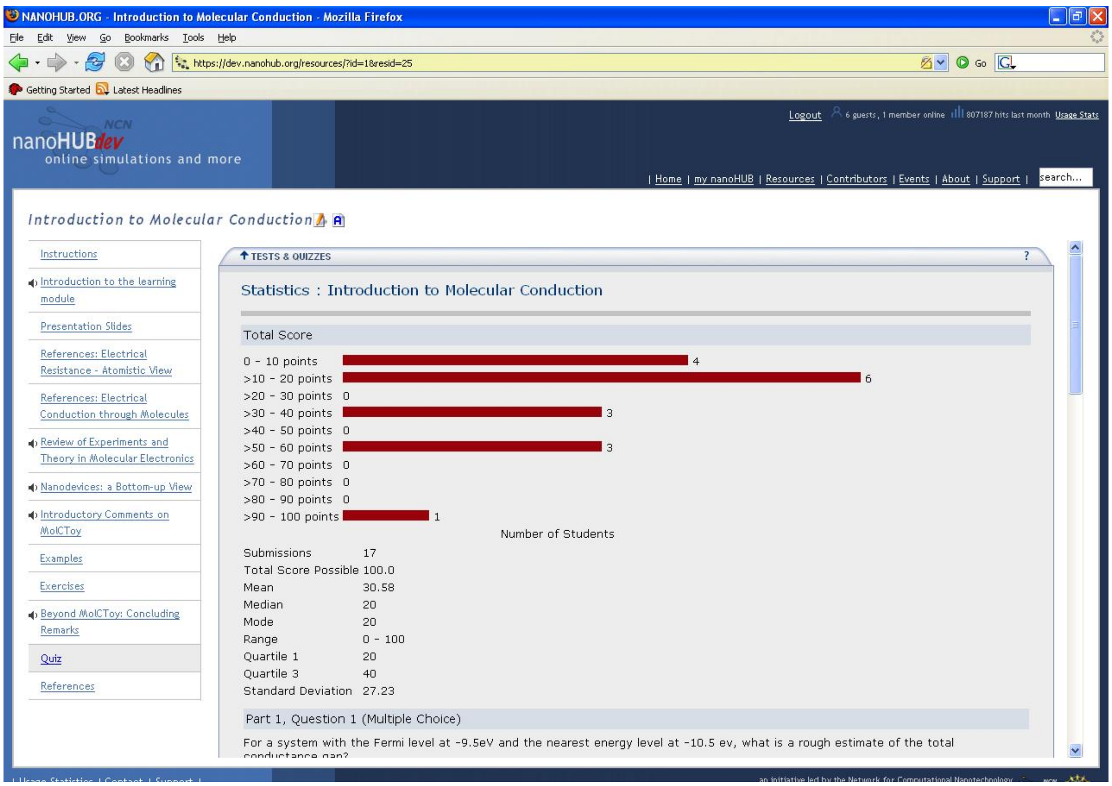

Fig. 2. nanoHUB learning module showing the reporting capabilities of the Sakai (Samigo) Assessment Engine. (Snapshot from our Development Site)

Continuous assessment of the learning outcomes is a key part of the NCN educational strategy. This assessment should not only include pre/post test analyses of student scores on various quizzes and exercises available as part of the learning modules, but also a complete analysis of usage statistics to derive better intelligence about the users. The nanoHUB has the capability to report usage metrics at very fine granularity. However, nanoHUB does not have the core capability as part of its infrastructure to track in-depth student performance data. In order to address this problem, the middleware team has started to integrate the assessment services offered through the Sakai Collaboration and Learning Environment into the nanoHUB. This work utilizes the service-oriented infrastructure offered by Sakai and is in the final stages of deployment. A snapshot of the integrated Sakai assessment engine from our development (DEV) site can be seen in Figure 2. All materials developed by NCN faculty and students will benefit from these assessment practices and usage statistics analyses.

Almost all seminars, presentations, and learning modules on the nanoHUB utilize the Macromedia Breeze technology and are inherently compliant with IMS [21] – the global e-learning specification. The combination of traditional learning materials such as voiced presentations with online simulations present major challenges to the furtherance of e-learning specifications. With the advent of highly cross-disciplinary fields like nanotechnology, the tools that are used on a regular basis in classrooms – such as course management systems – need to be more capable of handling advanced simulation tools within the learning environments. The model provided by NCN through the development and deployment of learning modules that incorporate advanced simulation tools is one of the first available models for such integration. This work has attracted some interest in the e-learning community. Here is an example of how the nanoscale vision is impacting work in the area of global e-learning specifications and standards.

3.3. Next generation cyber-tools for learning on the nanoHUB

Mobility and complementary convergence of devices and services will be key characteristic of scientific work in the future. Cyberinfrastructure and middleware are pervasive in almost every aspect of modern life. They are present in the increasing pervasiveness of mobile phones, broadband at home, high definition (HD) television sets, and even in the cars we drive. Advances in science, engineering, socio-cognitive understanding, and technology have launched the human race headlong into a revolution where the boundary between how information is constructed, stored, accessed, delivered, and understood has blurred. One critical characteristic of this impending revolution is that the time lapse between construction of data to delivery of significant scientific insights is steadily (and in many cases exponentially) decreasing. What is more breathtaking about this infant revolution is that the next generation of scientists – the so-called millennium generation or Generation-Z – currently in middle and high schools or just beginning college is accelerating this revolution to warp speed. Through the innovative use of emerging communication technologies and cyberinfrastructure-enabled social networks, and by thriving in a world that demands tremendous cognitive flexibility, students are sending a clear signal for the need of the educational system to reflect this on-going revolution. Yet, a significant part of our pedagogical approaches remain immune and continue to have their foundations in the pre-information age – if not in the pre-industrial era.

Fig. 3. nanoHUB seminars on iPods

NCN's vision for the research on next generation educational technologies is focused on expanding the role of nanoHUB as a cyberinfrastructure enabled discovery and learning ecosystem. All cyber-services that constitute the ecosystem are built on the fundamental premise that learning experiences of the future will be multi-sensory, engage multiple technologies and significant computational power invisibly, continuously, and will be completely engaging.

3.4. Podcast: Enabling ubiquitous availability of nanoHUB content

One of the key traits of the next generation of students is their need to be untethered and mobile coupled with the use of extremely small form factor devices. nanoHUB intrinsically requires the use of a browser for accessing any of its services. Over the past year, nanoHUB has introduced podcasts with video and audio that allow users to take nanoHUB content with them on their iPods^{TM} or mp3 players. The nanoHUB team is currently offering increasingly more content in this extremely versatile format (see Figure 3). Podcasts are being considered as a significant emerging pedagogical tool due to their ability to deliver content in formats that fit with students' lifestyles and technology choices [see 22, 23, 24, and 25 among several major publications on this].

4. CONCLUSION

This paper, by describing the contributions of the NSF-funded Network for Computational Nanotechnology's nanoHUB, has outlined how the nanoscale vision is impacting the teaching and learning arena. The development of new and innovative strategies such as the bottom-up approach for teaching concepts on electronic devices have resulted out of the research in the area of nanoscale science, engineering, and technology. Clearly, the start of the learning pipeline – namely the K – 12 community – needs more focused intervention. To this end, the nanoHUB team is working on a new portal entitled *nanoHUB for Kids* that attempts to introduce simulation based science into the K – 12 curricula and also provide resources for more informal activities that parents can use at home. Even at the undergraduate and graduate levels there is significant work that needs to be done. Reaching into traditionally underprivileged and underrepresented groups has been a great challenge. Through the use of cyberinfrastructure such as the one adopted by the nanoHUB, now we have a real chance to engage these communities. Future work in this direction still needs to be expanded and new assessment methods deviced.

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