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Toward Integrating Nanotechnology in the K-12 Science Curriculum: A Note of Hope in the State of the Union

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Abstract- Institutions of higher education throughout the United States must be prepared to provide high-quality professional development for K-12 teachers that encourages them to see connections between/among science, technology, engineering, and math (STEM) via study of the core concepts and various applications of nanotechnology. The development of an integrated science curriculum based on nanotechnology will enable STEM teachers to inspire students to view science as immediately relevant to their daily lives and, over time, worth pursuing as a major and a career. This paper addresses some of the challenges associated with the need to develop an effective method of institutionalizing interdisciplinary science education through the use of nanotechnology to design, develop, and test a multiple-level, inquiry-based educational model aligned with National Science Education Standards.

Keywords: Nanotechnology, Education, STEM disciplines, Teaching, Integrated science curriculum.

1. Introduction

Over the course of the last two decades, the U.S. has failed to keep pace with its global competitors in science and technology. President Obama's "Plan for a Strong Middle Class and a Strong America," released in conjunction with his 2013 State of the Union Address, emphasizes the need to create a STEM Master Teacher Corps to consist of 10,000 of the finest science and math teachers in the United States [1]. This portion of the Administration's plan is based on recommendations by the President's Council of Advisors on Science and Technology (PCAST) to develop a critical mass of educators who will collaborate with their peers to enhance STEM education in the nation's public schools: "The most important factor in ensuring excellence is great STEM teachers, with both deep content knowledge in STEM subjects and mastery of pedagogical skills required to teach these subjects well" [2].

The theory is sound in principle and noble in conceit: a relatively small cadre of teachers with the necessary preparation and inspiration will return to their communities to effect systemic change. Over the next decade, the ambition is to prepare an additional 100,000 STEM teachers with the aid of the philanthropic sector [3]. Nevertheless, given the lack of a budget to support the system of rewards and recognition that the President has in mind, it may not be possible to put this particular idea into practice. There is also the enormous weight of the reality of STEM education in the K-12 system in the United States to consider. While maintaining that well-qualified teachers are the best indicator of student achievement, the Committee on Prospering in the Global Economy of the 21st Century observed, "Many school children are systematically discouraged from learning science and mathematics because of their teachers' lack of preparation, or in some cases, because of their teachers' disdain for science and mathematics" [4]. Indeed, out-of-field teaching may be the single most important factor in the gradual decline in the test scores of American youth.

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Teachers without an undergraduate degree in science and without certification to teach it are, in fact, the "norm" in many schools throughout the country: "In grades 9-12, the chance of being taught math by an out-of-field teacher [is] 31%, and for physical science it is 63%" [5]. Furthermore, according to the National Center for Education Statistics, only six states require that parents be notified when their children are assigned an out-of-field teacher, and only seven states place a "ban or cap on the number of out-of-field teachers" [6]. Under these circumstances, it may be more surprising that students in the U.S. continue to score as well as they do than to read yet another report that they have fallen behind in STEM disciplines by comparison with their peers internationally. Against tremendous odds, roughly 6% of U.S. 15-year-olds yet managed to distinguish themselves as measured by the Programme for International Student Assessment (PISA) in 2006 [7]. The average U.S. score in science literacy had improved by 2009—when the nation's 15-year-olds ranked 24th among their peers in all participating nations [8].

In order to ensure that more students have the opportunity to learn significant STEM content, it will be necessary to educate-the-educators, especially as there is strong evidence that the lack of qualified teachers actively deters student interest and success [4]. If the STEM Master Teacher Corps is to succeed, it will need the committed support of professional investigators and qualified faculty members at the nation's institutions of higher education to develop an integrated science curriculum and effective pedagogical strategies.

Edward T. Foley and Mark C. Hersam (2006) believe that extensive nanotechnology education reform has the potential to "reverse the decay" in the "U.S. STEM educational pipeline" and overcome the widening gap in the high-technology talent pool between the United States and the remainder of the developed world [5]. A decade ago, Mihail C. Roco (2003) suggested that, in order to facilitate the integration of nanotechnology across the scientific curriculum, we must reverse the typical learning "pyramid"—wherein an understanding of the "broad connections" among the various STEM disciplines is gleaned only in the latter stages of graduate school [9]. Nevertheless, such an undertaking will require a radical re-thinking of the K-12 system—not only with respect to what is taught, but how. Existing curricula and pedagogical strategies effectively thwart students' ability to grasp "big ideas" because basic concepts in biology, chemistry, mathematics, and physics are taught piecemeal.

How can we enhance the ability of teachers to provide high-quality STEM education for all students—and thereby assure that all students will have the opportunity to learn significant STEM content? First, we must be willing to re-think and re-structure the K-12 curriculum and associated pedagogical strategies: the essential what and how of American public education. Second, we must admit that "who" matters, too: only highly skilled teachers are capable of preparing children to compete on a global basis and inspiring them to do so. If institutions of higher education begin working in earnest with the public school system to institutionalize interdisciplinary science education using the core concepts of nanotechnology coupled with standards-driven, inquiry-based, active learning strategies, we should be able to move toward a revitalized K-12 curriculum and make a significant difference in the quality of STEM education.

1.1. Past Experience

For those who may be reluctant to believe that change of such a revolutionary nature is possible, especially given the intransigency of the public school system in the U.S., I offer this brief history of a course of study now deemed essential: mathematics. Although Socrates had once used a lesson in geometry to prove the existence of "inborn knowledge" [10], in the 1920s, the discipline of mathematics was deemed suitable "for only a select few" by no less than William Heard Kilpatrick—one of the most influential "progressive" educators in the nation [11]. As a result, by the 1940s, U.S. Army recruits knew "so little math that the army itself had to provide training in the arithmetic needed for basic bookkeeping and gunnery" [11]. Perhaps calculus is still not regularly offered in public schools throughout the U.S.; nonetheless, algebra and geometry are by now firmly seated among the standards—thanks largely to the persistence of mathematicians and high school teachers.

Moreover, a teacher-driven integrated science program (ISP) that has sustained itself for more than two decades successfully added a unit on nanotechnology to the 9th-grade curriculum in chemistry as early as 2000 [12]. This fascinating change in course content emerged when the teachers realized that the ISP was working so effectively that they could afford to drop "some foundational topics" in favor of the new technology [12]. In their study, Larkin et al. (2008) attributed the longevity and prosperity of this instance of curricular reform to teacher leadership—the key ingredient in any attempt to transform the classroom [12].

2. Discussion

It is well to keep in mind that the National Center for Learning and Teaching in Nanoscale Science and Engineering (NCLTNSE) has been offering professional development opportunities for public school teachers since 2005 [13]. These two-day summer workshops have received impressive reviews from those in attendance, yet there has been no sign of extensive improvement in the K-12 system. Furthermore, although dozens of high-school teachers participate in the NCLTNSE's Materials World Modules Program, only four elementary/middle schools are involved, nation-wide—and a mere eighteen colleges and universities are listed as partners in developing modular instructional content to supplement pre-college STEM curricula.

In 2010, the National Science Foundation sponsored an International Benchmark Workshop on K-12 Nanoscale Science and Engineering Education (NSEE). In assessing the status of efforts to introduce NSEE into K-12 education, the authors of the "Workshop Report" concluded that progress "has been slow, largely because the focus on teaching to science content standards, developed independently by each state and often lagging the state-of-the-practice, effectively precludes the use of NSE materials" [14]. Indeed, concerted efforts have been made globally to develop educational modules that incorporate nanoscale science and engineering at all grade levels, owing to the realization that "nano-enabled technologies will be pervasive by the time students presently in the K-12 grades enter the adult world" (Murday *et al*. 2010). Despite the very great need for a well-educated and informed public, workshop participants concluded that the identification of appropriate standards and the development of teaching aids will prove ineffective unless teachers are "comfortable with the materials" [14].

2.1. Establishing Overall Goals

Obviously, if the long-range purpose is to create a critical mass of committed teachers in order to engage the instructional community in the development of a radically new STEM curriculum, institutions of higher education must play an integral role in the transformation—not only by better preparing future teachers but by actively engaging those already in the field. In order to begin the process, institutions of higher education should establish a set of specific goals in support of the President's Plan, such as the following:

> Goal 1: To use nanotechnology as a vehicle for enhancing the STEM content knowledge and pedagogical skills of science teachers;
>
> Goal 2: To develop, pilot, and refine a standards-based and inquiry-based curriculum module for teachers that will show how nanoscale concepts can be used to facilitate student learning of interdisciplinary core scientific concepts;
>
> Goal 3: To implement an innovative model of mutual mentoring between higher-education faculty and public school teachers in the area of nanotechnology;
>
> Goal 4: To expand outreach programs for the broader K-12 community in partnership with the area museums and other informal venues for science learning.

2.2. Learning Progressions for Teachers and Students

In 2009, Corcoran, Mosher, and Rogat published a report based on panel discussions held at the Center on Continuous Instructional Improvement (CCII) at Columbia University examining the work that has been done, thus far, on learning progressions in science, potential benefits of their application, and steps necessary "to flesh out a map of progressions for K-12 science" [15]. As the CCII Panel noted, one initial challenge concerns the identification of core science concepts that will form the progression. Lynn Bryan *et al*. (2007) have suggested that forming a consensus as to the "big ideas" to be addressed may pose particular difficulties in nanoscale science owing to the fact that it is a relatively new field of study [16].

Furthermore, although learning progressions typically move from the concrete to the abstract—the tangible to the invisible—nothing at the nanoscale is directly observable without sophisticated instrumentation. Thus, modeling and training in visualization via the required instrumentation will be required if teachers and their students are to be able to "see" at the nanoscale—whereas few, if any, public schools in the United States have access to this equipment. Nevertheless, many institutions of higher education are in a position to provide wider access to their instrumentation via the internet. Since electron microscopes, Raman spectrometers, and the like can cost a university anywhere from several hundred thousand to several million U.S. dollars, it behooves these institutions to seek a greater return on their investments through the general advancement of knowledge. Again, it is clear that the involvement of institutions of higher education will be key to the success of any real innovation, much less revitalization, of the science curriculum available to U.S. students.

2.3. Active Learning

According to Foley and Hersam, "The National Academy of Engineering (NAE) has described the necessary attributes of the engineer of 2020 as strong analytic skills, practicing ingenuity, creativity, communication, a command of the principles of business and management, leadership, high ethical standards, professionalism, dynamism, agility, resilience, flexibility, and engaging in life long learning" [5]. "Active learning"—widely used with considerable success in the international business community in recent years—will be necessary to develop the kind of leadership required for the transformation of the preK-12 educational system in the United States. In broad terms, "active learning" entails group-work designed to inspire inquiry to address real-world problems.

2.4. Summer Teaching Institutes

With the assistance of higher education faculty, teachers selected for the Master Teacher Corps could initially participate and potentially lead professional development workshops during the summer with a three-hour follow-up session to be conducted two weeks afterward. The curriculum modules for such an institute could include 1) an introduction to matters of scale with a hands-on activity involving the creation of models designed to illustrate the principles involved; 2) a discussion of size-dependent properties, e.g., color, surface area, forces. (See Table 1 below.) By the end of the institute, teachers should be able to develop lesson plans and exercises for students designed to introduce them to nanotechnology for the strand "History and Nature of Science"—a National Science Education Standards requirement they will readily recognize as relevant to their teaching across all scientific disciplines. Among many other possibilities, teachers could consider introducing nanotechnology as the latest in a series of historic scientific breakthroughs.

Table 1. Sample summer institute curriculum module

Session 1	Session 2	Session 3	Session 4	Session 5
Pre-Test				
Nanoscale	Size-dependent properties (color)	Size-dependent properties (surface area)	Size-dependent properties (forces)	Instrumentation & applications
Creating Models to Illustrate Scale	Demonstrations and training in online access to instruments	Creating models to illustrate surface-area proportions	"Lily v. Petal Effects" as illustrations	Tour of HIE laboratories
Real-world problem: how best to demonstrate nanoscale for high school students	Real-world problem: how best to illustrate color as a size-dependent property	Real-world problem: how best to demonstrate surface area as a size-dependent property	Real-world problem: how best to describe ionic forces	Post-test; post-institute survey
Develop lesson plan and exercises for students introducing nanotechnology for "History and Nature of Science"				Focus group interviews

2.5. Shadowing

Members of the Master Teacher Corps could be paired, according to their interests, with professional investigators at institutions of higher education to work on specific hands-on projects during the summer and/or throughout the academic year. In order to emphasize the widespread practical applications of nanotechnology, participating teachers might find it particularly beneficial to observe product samples from industry being visualized and characterized in the laboratories of research institutions. Through the process of "shadowing," the teachers will obviously learn additional science content, but they should also be far better prepared to share their findings with students and others in public venues: peer-to-peer presentations in their respective schools, science fair competitions, and a variety of events sponsored by area museums.

2.6. Public Presentations

It is the mission of many museums nation-wide to ignite a passion for science, technology and math in a dynamic, interactive environment. As part of a "capstone" project resulting from the summer institute, public school teachers should be able to demonstrate what they have learned for their students and other teachers, as well as members of the general public.

2.7. Evaluation

Both formative and summative evaluations of the extent to which the goals have been met must be conducted annually in order to garner private support and engage the public as a whole. The data collected should come from instruments designed to obtain qualitative and quantitative information. Evaluation questions should include factors that hindered or facilitated implementation of new curricular or pedagogical strategies, as well as the impact of the initiative on teacher outcomes. Other evaluative activities could include third-party observations conducted during the summer institutes and in the public school classrooms; surveys to assess teacher content knowledge, as well as motivation; focus group interviews during which teachers are asked to reflect on their participation; and the sharing of program documentation.

3. Conclusion

Despite the challenges, it would be unconscionable to effectively deny the public access to information that will be critical to making informed decisions concerning its own welfare in the decades to come. Essentially, there must be a way to circumvent—if not cut—the bureaucratic red tape and push toward an integrated curriculum module that will facilitate the learning process for both teachers and students. If we provide high-quality professional development for high school science teachers that encourages them to see connections between/among STEM disciplines via study of the core concepts and various applications of nanotechnology, they will be better prepared to inspire students to view science as immediately relevant to their daily lives and, over time, worth pursuing as a major and a career.

Carl Wiesman, former Associate Director for Science at the White House Office of Science and Technology Policy, has urged educators to adopt techniques that help students to "think like little scientists" [17]. Interestingly, this should not be difficult as many experts in child development well know. The realization that children inherently seek to understand the world about them by observation, experimentation, and reasoning is at least as old as the work of Jean Piaget (1896-1980) and has been widely promoted through the Montessori system in the U.S. If this is indeed the case, it should be no more difficult for people of any age to comprehend the core concepts of nanotechnology than it is for them to master observations that are basic to science. For example, first-graders watching a Gecko clinging to the glass sides of a terrarium or observing water streaming from the leaves of a lotus are viewing phenomena simultaneously relevant to nanoscale structure and the life sciences. Of course, the degree to which individual students can understand the details of causality—not to mention the mathematics that underpin the ability to predict results at the nanoscale—will differ, at least partially, on the basis of their intellectual maturity.

The real difficulties then lie in who will educate-the-educators and under what circumstances will they be able to work together in order to develop a fully fleshed-out integrated science curriculum appropriate for students at each grade level. Courageous and dedicated high school science teachers have in some cases done it on their own: as early as 2000, chemistry teachers at a high school in Wisconsin working toward an integrated science curriculum dropped some of their "foundational topics" and added a unit on nanotechnology [12]. The NSF has sponsored numerous workshops, conferences, and professional development programs with these objectives in mind. The impact of a Master Teacher Corps of 10,000 would certainly be felt, especially if the corps were broad-based and not limited to teachers at schools that are already high-performing. Much, however, will ultimately depend upon the commitment that institutions of higher education are willing to make to K-12 education. Given the decades of disgruntlement concerning the unpreparedness of entering freshmen, it would seem that college/university administrators and faculty would welcome the opportunity to make a difference; however, much time has been wasted in "finger-pointing" and little attention has been paid to the responsibility that colleges and universities have for ensuring the success of K-12 teachers and, in turn, the quality of education they are able to offer children. Here, again, there may be a note of hope to be found in the President's 2013 State of the Union Address—this time in the form of a "stick" as opposed to a "carrot." President Obama has called on Congress to "consider value, affordability, and student outcomes in making determinations about which colleges and universities receive access to federal student aid" [1].

A great deal of research has been conducted, and the groundwork has been laid for a revitalization of STEM teaching and learning using nanotechnology as the basis for a new K-12 integrated science curriculum. The framework, hardware, and expertise needed to disseminate information concerning the applications and implications of nanotechnology are already in place at research institutions, and these institutions must now give serious consideration to the long-term value of a further investment in the intellectual advancement of public school educators and, through them, the enhancement of awareness among the general population. Nanotechnology could provide a unique context for helping teachers develop both content knowledge and pedagogical skills. It is furthermore crucial that the general public be well informed concerning increasingly pervasive nano-enabled technologies that offer tremendous potential benefits but may also have negative environmental and societal consequences.

Who will educate-the-educators? A Master Teacher Corps of 10,000 will not suffice. Who will prepare the 100,000 new STEM teachers—regardless of the source of funding? The responsibility clearly falls upon the institutions of higher education whose obligation it is to provide the professional development that current teachers—their *former* students—will need in order to equip children in the K-12 public school system—their *future* students—with the education they need in order to prosper.

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