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Nanotechnology Education for the Global World: Training the Leaders of Tomorrow

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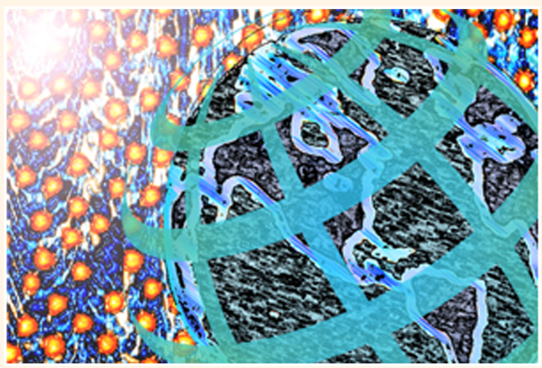
ABSTRACT: **Nanoscience is one of the fastest growing and most impactful fields in global scientific research. In order to support the continued development of nanoscience and nanotechnology, it is important that nanoscience education be a top priority to accelerate research excellence. In this Nano Focus, we discuss current approaches to nanoscience training and propose a learning design framework to promote the next generation of nanoscientists. Prominent among these are the abilities to communicate and to work across and between conventional disciplines. While the United States has played leading roles in initiating these developments, the global landscape of nanoscience calls for worldwide attention to this educational need. Recent developments in emerging nanoscience nations are also discussed. Photo credit: Jae Hyeon Park.**



GLOBAL WORLD OF NANO

Nanoscience and nanotechnology are among the fastest growing fields in science and engineering and are leading to breakthroughs in energy, medicine, environmental science, biotechnology, and other areas. One of the hallmark features of these fields is an interdisciplinary viewpoint that integrates traditional subjects such as chemistry, physics, and biology in order to study and to exploit phenomena at the nanoscale.[1] Indeed, materials with nanoscale dimensions can have dramatically different properties than larger (and smaller) counterparts, exhibiting features that blur quantum and classical physics. All of these features continue to fascinate scientists and engineers; there is growing recognition that nanotechnology is poised to become a major part of the world economy.

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One particularly interesting aspect of nanotechnology is its growing impact worldwide. The United States was the early leader in nanotechnology, catalyzing the development of the National Nanotechnology Initiative to implement national policy.[2] While the United States remains a key leader, especially in terms of innovation, other parts of the world are also moving forward rapidly and investing heavily in these areas. The European Union has made nanotechnology a top scientific priority, as evidenced by initiatives such as the €1 billion Graphene Flagship project sponsored by the European Commission.[3] Also striking is the rapid growth of nanotechnology in Asia and its global competitiveness. Notably, there have been growing numbers of international collaborations between research groups that span the globe (as often presented on the pages of *ACS Nano*). Taken together, these indicators point to an increasingly worldwide ecosystem of research and innovation in nanoscience and nanotechnology.

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Another defining characteristic of nanoscience research is that the distance between fundamental discovery and application is unusually short. Indeed, in nano*science* and nano*technology*, the distinction between the two is even more artificial than in other fields. Consequently, we currently see a large number of nanotechnology-based spin-out companies where nanoscience graduates have high employability.

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Established knowledge-based companies also increasingly look for employees who are able to operate between disciplines to act as (universal) translators. This increased value of communication skills may be a consequence of steadily accelerating technological development, which blurs the boundaries between traditional disciplines and renders old specializations obsolete. This weighting also points to a sweet spot for nanoscience undergraduate curricula, which should provide a broad, yet challenging, introduction to both "hard" and "soft" natural-science disciplines with some specialized topics early and more at the graduate levels.

In order to achieve the full potential of nanotechnology in society, it is also important to reflect on how the globalization of nanotechnology impacts nanoscience education and training. Indeed, global cooperation has been cited as an important factor in developing effective educational programs.[4] Yet, most discussions of nanotechnology education and training have focused on learning design and curriculum, in part, reflecting the challenges of defining common learning goals in a field that is constantly evolving and blurring traditional subject boundaries. Indeed, at the same time, a broader discussion is needed that identifies a roadmap for how nanotechnology education can lead to a well-developed workforce that is prepared to meet not only technical needs but also the global challenges to succeed in the 21st century. These challenges include understanding and working across cultural differences as well as broadening access to diversify the talent pool and, ultimately, the workforce. The goal of this Nano Focus article is to discuss the current status of nanoscience and nanotechnology education, to highlight innovative global practices that provide useful models, and to recommend future actions that could reinforce current practices and further strengthen nanotechnology education and training worldwide.

NANOSCIENCE AND NANOTECHNOLOGY EDUCATION

Education has long been recognized as an important factor for growing the fields of nanoscience and nanotechnology and solidifying and expanding their roles in the global economy.[5] In many countries, there is growing interest in developing educational programs across the full spectrum of educational levels from K−12 (Figure 1) to postgraduate studies.[6,7] Various formal and informal educational practices are being designed and tested that promote general awareness of nanoscience and nanotechnology as well as provide advanced learning and skills development, including through group learning and peer assessment.[8] Early efforts have also developed rubrics for assessing such educational programs. Due to the interdisciplinary nature of nanoscience, one common challenge has been developing standard curriculum features, with much debate about the effectiveness of integrating nanotechnology concepts into existing coursework *versus* creating new courses for nanotechnology.[9−11] Course development, teacher training, and related issues are also being addressed.

Photo Credit: Jia Ming Chen

Figure 1. Middle and high school students spend time at the California NanoSystems Institute at UCLA running nanoscience experiments. High school teachers from over 100 schools and 30 school districts are trained, networked to one another, and supplied with kits for their classrooms. Graduate students, postdocs, faculty, and staff run, expand, and improve these fully subscribed outreach events on a continuous basis.

In addition to these pedagogical features, there are outstanding questions about the directions of nanoscience and nanotechnology education in general. One suggestion has been to focus on developing effective learning platforms to train the next generation of scientists. Such efforts call for long-term strategies that incorporate more personalized approaches to guide student development.[12] Indeed, the successful growth of the nanotechnology sector will require a broad approach to skills training, preparing students for different levels of careers in technical and nontechnical positions, and developing pathways to grow the available pool of talent by attracting more diverse groups of students.[13] Whereas nanoscience and nanotechnology education at higher levels has traditionally focused on scientists and engineers in research positions, the growth of nanotechnology as an economic force will include a wider range of individuals with different scientific and nonscientific backgrounds and training needs.[14] A stratified and coordinated educational framework should be devised that lays out the workforce growth plans for the entire field, including leadership development. In many organizations, leaders without scientific backgrounds are responsible for making important decisions about nanotechnology projects, and there is significant room to improve by developing future scientific leaders who combine strong technical backgrounds in nanotechnology with management training and global understanding.[15]

From this perspective, the challenges of nanoscience and nanotechnology education in the global world are multipronged, and meeting these needs requires creative and innovative learning models that blend classroom learning with cross-sector training and international experiences. Some of the best examples have been presented at the undergraduate level,

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Photo Credit: Hyejin Kim

Figure 2. Over 600 students from schools in South Korea, Japan, Nigeria, and the United States of America attended the 2013 Molecular Frontiers Symposium at Korea University in Seoul, South Korea. Four Nobel Laureates and many other distinguished scientists from across the world attended the event and interacted with the students. A key feature of the symposium series is a set of extensive question and answer sessions through which students have the chance to connect with scientific luminaries.

and the basic principles of these programs offer a framework that can be applied across different levels and for a multiplicity of purposes. For over a decade, nanocenters have provided platforms for facile experimentation on a broad range of educational models, yielding a large library that could be mined for components for future programs.

CROSS-DISCIPLINARY LEARNING MODELS

In this section, we discuss innovative learning models that are being applied at the undergraduate level in order to train future leaders at the interface of engineering and management. While the programs are not strictly focused on nanotechnology, many graduates pursue nanotechnology-focused careers and they provide examples of important factors that should be considered in the nanotechnology field. Moreover, they represent the growing trend of holistic learning, which integrates coursework across disciplines, promotes foreign experiences, and encourages industrial internships.

Many universities have combined business and engineering degrees and/or added significant components of one program to the other. The goals of these programs are to integrate technology and business to solve important commercial, social, medical, environmental, and other problems. Shorter programs and classes have achieved notable successes, as well, such as the Biodesign Innovation course at Stanford University and the technology commercialization program of the University of Pennsylvania, Wharton School of Business.[16,17]

In some programs, graduates are required to demonstrate foreign language proficiency, as well, to prepare for the global reach of these technologies. At Nanyang Technological University in Singapore, the Renaissance Engineering Program (REP) was started a few years ago in order to train the "Engineering Leaders of Tomorrow". Students join the program directly from high school and earn an undergraduate degree in an engineering specialization along with a graduate degree in technology management. As part of the track, students spend one year at an elite partner university in the United States or Europe and also partake in an extended company internship. In Singapore, it is the first educational program of its kind, and its collective features set a new precedent for undergraduate education in Asia.[18] At later career stages, programs such as the U.S. National Science Foundation Innovation Corps (I-Corps) Program give academic scientists and engineers basic but intense training in entrepreneurship.[19]

Based on these examples and other educational practices, we propose a set of recommendations that should be taken into account when planning for nanotechnology education and training in the 21st century global world.

RECOMMENDATIONS

Inspire Students To Envision What Is or Could Be Possible. Every day, we witness the incredible power of nanotechnology in our daily lives. From our new computer to some of the most successful cancer therapies on the market, nanoscience plays key roles in driving forward innovation. Yet, how often are these inventions recognized as nanotechnology (or "nano-enabled" technologies) among the public? We need to develop creative ways to highlight that nanoscience and nanotechnology impact our world and change it for the better. Possibilities include a greater focus on nanotechnology applications in courses or hands-on laboratory experiences that tie in with class concepts. Even before reaching the classroom, students should have positive views of nanoscience and the potential it holds. Successful learning practices start with capturing the imagination of students.[7,20] Communicating the remarkable features of nanoscience in a simple and clear way to the mainstream public would go a long way toward achieving this goal. The NBC LEARN series on nanotechnology is an example of an excellent program that addresses the public while also providing a tool to augment didactic presentation of course content.[21]

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Promote Role Models Who Impact Society. While nanotechnology applications can demonstrate promise, it is even more important to present role models to students in order to encourage them to reach similar heights. In sports or even the tech world, students have role models that encourage them to continue practicing and improving, oftentimes in extreme and methodical ways that push boundaries in order to make breakthroughs; we have started on this campaign here, with occasional Conversations with leaders in nanoscience and nanotechnology.[22−27] From an educational perspective, the tech world is a particularly good example because successful entrepreneurs such as Steve Jobs, Elon Musk, Sheryl Sandberg, and Mark Zuckerberg have captured the public audience and inspired countless students to think beyond the classroom. In nanotechnology, similar role models can inspire students with the many opportunities available in the field. Indeed, the ingredients are already there. While popular media currently focuses on tech pioneers involved in graphical interfaces and hardware products, there are also many successful scientists and entrepreneurs who have made groundbreaking achievements in nanotechnology and that paint similar success stories. Developing popular platforms to highlight these leaders and to allow them to interact with students would be a significant improvement.[28] As one example, the Molecular Frontiers Foundation has created a series of conferences in Europe and Asia that bring together world-class speakers, including many Nobel Laureates, and local high school students (Figure 2).[29] The goal of the conferences is not only to present cutting-edge research but also to inspire the students and to encourage them to interact with the scientists. One creative aspect of the Molecular Frontiers conference format is that scientists have been portrayed as superhero life-size caricatures that bring joviality to the learning experience and give students an impression of how just impactful nanotechnology research can be.

Encourage Global Collaboration. As part of the educational experience, students should conduct scientific research in different cultural environments and be exposed to different viewpoints, backgrounds, and approaches. Nanotechnology research and development is truly global. Early exposure to these trends will better inform students about career opportunities and give them ideas about how to work together in teams across disciplines and cultures. A growing number of partnerships provide international experiences for nanoscience and nanotechnology students. We have all participated in both formal and informal programs. Still, only a small minority of students spend time training outside their home countries. Partnerships create opportunities for students to participate in coursework and research opportunities at other universities. Some Research Experience for Undergraduate (REU) programs offered by the U.S. National Science Foundation have been sponsored overseas or with international partners, yet much greater progress remains possible. Indeed, with recent news of the new Schwarzman Scholars program for social science graduate students in China and other well-known fellowship programs such as the Rhodes, Churchill, Fulbright, Marshall, and Gates-Cambridge Scholarship programs, there are excellent models that can be applied toward developing similar levels of targeted educational opportunities for students in the nanotechnology field. At the same time, giving a broader range of students the opportunity and support to obtain international experiences is another important goal.

Support Early Exposure Inside *and* Outside of the Laboratory. For many students, nanoscience and nanotechnology are about working in a lab doing scientific research. While this activity is common, its generalization could not be farther from the truth. There are many possible ways to get involved in nanotechnology, from instructional education and hands-on training to entrepreneurship and manufacturing. Holistic approaches that integrate these different possibilities, while providing targeted career development, would greatly benefit students and the overall goals of nanotechnology education. Developing a strong workforce infrastructure for nanotechnology will ultimately require stratification based on career interests and skill levels, among other factors. In order to achieve the best outcomes, it will be beneficial for students to have experiential learning to acquaint them with the different possibilities. Ultimately, successful implementation of nanotechnology education and training programs across the entire sector will require a long-term strategy that not only provides individual students with cross-disciplinary knowledge but also produces students with complementary skill sets who can work together in teams in order to tackle the complex problems facing society.

Communication Across Fields. Finally, one of the great strengths of the nanoscience and nanotechnology communities is that we have taught each other how to communicate across fields, to look at and to leverage each other's approaches, and to address the key issues of a multitude of fields.[30−33] As a field, we are increasingly viewed as problem solvers in science and technology, developing new tools, materials, methods, and opportunities. Bringing this aspect of our field to students (and scientists and engineers at *all* levels) will have significant impact on the world around us and our ability to make it better.

CONCLUSIONS AND PROSPECTS

We have an enormous opportunity ahead in enhancing education in nanoscience and nanotechnology, in expanding the impact of and support for our field. Exposing students to and ultimately creating an educated citizenry regarding the possibilities of advances ahead, both in exploring new unseen worlds as well as in addressing the challenges the world faces, will be important in making both into realities. Nanocenters around the world have special roles to play in developing these educational experiences, reaching out to the public, sharing ideas on what works and what does not, tying together international efforts, and in exchanging both students and practitioners.[34] Further regular communication between these centers and connecting to other local efforts around the world would accelerate these advances.

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We have also developed special capabilities in communicating across fields, in sharing each other's approaches and problems, and in applying our tools outside of our field. These special skills are going to be required by other fields but to a

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great extent have not yet been realized. By bringing the greater scientific, engineering, medical, and other fields together through nanoscience and nanotechnology, and our deliberate cross-training in approaches and communication, we will advance and impact these fields, as well.

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Notes

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