Some Food for Thought on Nanoeducation

Twenty years ago, the development of nanotechnology-focused education programs was not on the radar of most academic institutions. The prototypical nanotechnology education path involved students majoring in a classic science (*e.g.*, chemistry or physics) or engineering (*e.g.*, electrical or chemical) discipline as an undergraduate student, followed by students joining research labs working on nanotechnology-related projects in pursuit of their doctorate. However, this educational approach may no longer be appropriate, as students may not want to pursue graduate training and may wish to focus on nanotechnology in an undergraduate curriculum. Additionally, many nanotechnology companies may only require staff with technical experience acquired at an undergraduate level. These rationales have led many universities to build nanotechnology-focused undergraduate programs.

Advocating nanotechnology-focused undergraduate programs can face a variety of problems. First, university education can be dramatically different between different countries, where the logistics of the program may vary between North America, Europe, and Asia because of the organization of the education system within each continent. In Europe, for example, there is not just one kind of undergraduate program. For countries participating in the Bologna agreement, two distinct degrees are involved where typically three years are spent working toward the bachelor's degree, and an additional two years toward the master's degree, which makes the students qualify as a graduate student. Technically speaking, bachelor's and master's programs are distinct, and thus need to be independently comprehensive. Second, building a functioning and successful undergraduate nanotechnology program is not a simple matter because the field is inherently interdisciplinary. The need to include basic courses such as introductory chemistry, physics, organic chemistry, and other relevant basic science courses in the curriculum may make it difficult for students to complete their degree in a limited time frame. This constraint also complicates the design of an optimal curriculum that provides basic skills for a nanotechnology student to excel. Such issues have the highest practical relevance. Without a clear definition of what a degree in "nanotechnology" involves, industry will be initially hesitant to hire graduates and that will make these students less competitive for jobs.

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There are also significant challenges in preparing those students interested in academic careers. While it is obvious that a student with a bachelor's degree in ancient history is unlikely to be admitted to a physics graduate program, it is less clear for degrees in nanoscience. Does a bachelor's degree in nanoscience automatically qualify for admission to any graduate program in natural science, engineering, *etc.*, and would students have the background to start doing innovative nanotechnology research immediately? Unless clear criteria for validation are defined, a switch for students between different programs may be difficult.

Different types of nanotechnology undergraduate programs have developed in the past few years. In countries where only one degree is sufficient, such as the United States, students can enroll directly into a four- or five-year nanotechnology program. Specialization can also be introduced at distinct periods. In the United States, for example, students can take general science and engineering courses in their first two years followed by specialization in nanotechnology. In Europe, as an alternative example, nanotechnology-related programs exist at the bachelor's as well as at the master's level. A student can, in principle, first obtain a bachelor's degree in a "classical" discipline such as physics, and later continue

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with a master's degree in "nanotechnology," and *vice versa*. These examples already indicate the practical difficulties. These programs appear to have developed organically, individually driven by different universities. Universities that have a critical mass of researchers working in the nanotechnology field want to educate students in their respective field, which has led to proposals to develop an attractive program for incoming students. University administrators (as well as local governments) tend to like the field of nanotechnology because it adds novelty to the curriculum, is trendy and sexy, and has commercial appeal. While most professors working in the field are also positive toward such programs, they soon discover the inherent complication of assembling coherent, compatible, and comprehensive curriculums. In contrast to most classic science or engineering programs, which follow relatively unified general educational guidelines, a survey of most of the current nanotechnology programs reveals a lack of a similar unified list of courses, topics, and teaching materials. This inconsistency in material covered by these nanotechnology programs leads companies and graduate programs to question what students actually learn upon graduating from these programs.

There are major challenges moving forward. First, and foremost, there is a need to organize, develop, and agree upon a nanotechnology curriculum. This could be the focus of national meetings from major societies. A good example of unification of the education process is that undertaken by US-based biomedical engineering programs. The Biomedical Engineering Society has education forums at the Society's meetings where representative from biomedical engineering departments discuss curriculum matters. While variability between programs remains, the education community continues to discuss and to develop the courses, textbooks, and other teaching materials. Such a collaborative approach to developing course materials would be beneficial not only to the nanotechnology programs but also to the nanoscience community as a whole because it would force its members to evaluate and to synthesize the core principles and concepts of the field. Although education programs do evolve on their own, as a nanotechnology community, we must build the foundation that anchors the evolution of the education process. The biggest obstacle may be in lowering the walls between different disciplines (even between chemistry and physics), which still are surprisingly strict in many countries. Second, there is a need to develop excellent nanotechnology textbooks that outline the fundamental principles of the field for a unified educational experience. Using a chemistry program as an example, there are many textbooks (*e.g.*, *Introduction to Chemistry*, *Inorganic Chemistry*) written for students at the undergraduate level. While there are nanotechnology-focused books that can be used for education purposes, many of them are not written for first- or second-year undergraduate students and they do not have detailed problem sets that allow students to apply the concepts covered in the text. Third, feedback from industry is required. Is there a need for graduates with "nanotechnology" degrees? Industry is the likely recipient of a majority of graduates.

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Nanotechnology and nanoscience will continue to lead to new discoveries and to excite new minds. From an educational perspective, we must begin to consider what defines an educated nanoscientist or nanotechnologist and to develop the requisite programs and tools. It is time to start the dialogue on the best strategies to educate the future generation of nanotechnologists!

Finally, we invite you to join us at two events at the American Chemical Society national meeting next month in Dallas, Texas. We have again organized a symposium jointly with *Nano Letters* featuring our two journals' editors and advisory board members with talks related to the meeting theme; in Dallas, our symposium is on "Nanomaterials for Energy" and will be held prior to the Kavli Lectures on Monday afternoon. On Monday evening, we will host a "Discussion on Investigating and Reporting Research Misconduct" to continue the lively discussion sparked by our October 2013 editorial.[1] The discussion event will be held Monday evening and all are welcome. The location will be announced in the online program as well as on our twitter feed (@acsnano). We hope to see you at both events in Dallas!

Disclosure: Views expressed in this editorial are those of the authors and not necessarily the views of the ACS.

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REFERENCES AND NOTES

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