Nanotechnology Fellows Program: Preparing Undergraduate Students for Careers in Nanotechnology

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Introduction

From microscopy to materials synthesis, the demand for expertise in nanotechnology is not only growing, but it also spans multiple disciplines and encompasses a variety of careers.[1] The requisite education and training typically occur at the graduate level which limits undergraduates' access to cutting-edge jobs and many companies' workforce options.[2] Meaningful nanotechnology undergraduate education is difficult to achieve because: (1) science and engineering curricula are already full; (2) practical, hands-on experiences require extensive training on complex, expensive equipment; and (3) necessary fundamental concepts and knowledge – if taught at the undergraduate level at all – are introduced in late junior or senior year only.[3,4] Closely related to the demand for expertise is the knowledge required to initiate the innovation to venture process.[5,6] Specifically, students in these spheres have limited understanding of the processes behind intellectual property protection and the steps to moving innovative ideas from the laboratory to the market. We tackle these challenges with an undergraduate Nanotechnology Fellows Program. The program uses an interdisciplinary practicum approach to prepare undergraduates for careers in emerging technologies.

Nanotechnology Fellows Program Overview

The goals of the Nanotechnology Fellows Program are to foster student awareness, interest, and knowledge of nanotechnology topics, equip undergraduate students with the skills and experiences necessary to pursue careers in emerging technologies, and nurture excitement about science and engineering using the fascinating tools and advancements in nanotechnology research. The program includes a summer program with tutorials and hands-on training, in-person and online seminar courses ("Nanotechnology Devices & Systems: How They are Made, Measured, and Monetized" and "Connecting Nanotechnology to Your World") during the academic year, long-term, interdisciplinary research projects, nanotechnology equipment specialization projects, and mentorship and training with graduate students, professors, research scientists, and equipment vendors. The program is interdisciplinary with students and professors from multiple departments and schools across the university; topics include fabrication, characterization, and commercialization. The program is led by professors from three departments: mechanical and aerospace engineering, electrical and computer engineering, and engineering management and systems engineering.

Key features of the university's School of Engineering and Applied Science (SEAS) are relevant to understand the program setting and its applicability to other university/institutional settings. The university is private, and the class sizes are small (~15 students in a class). The average graduating class size per department is approximately 40 students. The student body is a tight-knit community, resulting in part from programs like the New Student Getaway for incoming freshmen and mentoring in the Student Peer Advisory Network. In 2015, a new nanotechnology facility opened. The Nanofabrication and Imaging Center is designed for both research and teaching purposes, and there is a dedicated teaching nanotechnology laboratory which is designated exclusively for student teaching and training purposes. Undergraduate research is strongly supported with the Dean's Office funding a Summer Undergraduate Research Experience program and an annual Research & Development Showcase featuring a student research poster competition.

The Nanotechnology Fellows Program targets freshmen and sophomores to influence students early in their academic careers, establish program longevity, and enable scaffolded and module-based learning. Program recruitment starts about one year in advance of the summer program. The program instructors give talks to incoming students and their parents describing the program's features and benefits. The talks take place during the university orientation week and are repeated at the beginning of the academic year in the SEAS "Meet the Faculty" seminars attended by all SEAS freshmen. The program leaders also hold informational office hours in which students ask questions and discuss the program. The program application is due in early February and consists of a resume, written statement, peer recommendation letter, and university faculty/staff recommendation letter. Applicants are asked to use these components to demonstrate the following:

- Why the applicant wants to be a part of the fellows program and what he/she will contribute to the program.
- Commitment to advancing science and engineering by being engaged in nanotechnology, contributing to the program community, and teaching/mentoring.
- Potential for success in the mentorship, training, and communication components of the fellows program.
- Enthusiasm for science/engineering.
- Participation in extra-curricular and co-curricular activities, particularly in engineering, science, math, and technology activities.
- Peer leadership and capacity to contribute to a diverse fellows program.

Applicants must be in good academic standing, but grade point average is specifically *not* considered in the review process since GPA is not an indicator which aligns with the program goals. Grades may be an indication of success in the traditional classroom setting but do not necessarily represent students' enthusiasm and their potential for leadership, mentorship, and communication. Program leaders select finalists from the applicant pool, and finalists are interviewed by a panel including upperclassmen peer mentors, a university diversity administrator, an outside nanotechnology specialist from industry or government, and the program leaders. For the first cohort, eight students were selected to participate in the program.

In each of its components, the program uses scaffolding as well as active, problem- and project-based, and peer learning to make graduate-level knowledge and skills accessible to undergraduate students. The program does not attempt to develop and test new learning approaches and resources. It uses methods which have demonstrated success and resources developed through other programs and projects, many of which were funded by federal agency program grants design to generate such resources. The fellows program utilizes, synthesizes, and applies resources in order to educate and train the future workforce.

The Nanotechnology Fellows Program is coupled with two nanotechnology courses. The curricular requirements are minimal. They do not overburden students during the academic year, and they integrate nanotechnology examples directly into students' core (major) curricula, thus linking emerging technologies to fundamental concepts. The courses are open to students of all majors. The first course, a one credit-hour seminar titled "Nanotechnology Devices & Systems: How They are Made, Measured, and Monetized," precedes the summer session. The course is team taught by three professors from different disciplines, and it has three modules on fabrication, characterization, and monetization. The modules include theory and examples of applications. Each module also includes one guest speaker who has expertise in the topic and presents examples of his/her work. The second course, titled "Connecting Nanotechnology to Your World," shows students how nanotechnology research and development examples are linked to their core (major) disciplines. For example, the vibration of an atomic force microscope cantilever is linked to concepts in the physics and differential equations courses. The course culminates in a project in which students construct their own homework/exam problem, lab activity, or case study connecting a nanotechnology example to one of their core (major) courses. The culminating project is then provided to the instructor of the relevant core course, and he/she can use it in the course, allowing many more students to gain exposure to nanotechnology.

The summer session of the Nanotechnology Fellows Program is eight weeks long. Students participate in tutorials, workshops, lessons, mini-projects, and hands-on training activities for four days a week, and they focus on a research project for one day a week. The program consists of units covering core nanotechnology fabrication and characterization techniques. Each unit includes background information lessons, research seminars, and hands-on activities. The units are: soft lithography and microfluidics, computer aided design for nano-device development, microscopy, electron beam lithography, finance, and sustainability. The units are taught by the program leaders. The fellows receive hands-on training on the following fabrication and characterization tools and techniques: photolithography, electron beam lithography (Raith Pioneer), scanning electron microscopy (Zeiss Sigma VP), and atomic force microscopy (Asylum Research Arc 2). Hands-on trainings and activities are conducted in the university Nanofabrication and Imaging Center and Institute for Nanotechnology; they are guided by research scientists, lab managers, and student mentors. The fellows program is integrated into the nanotechnology teaching and research facilities' staffing and mission, thus demonstrating a deep level of commitment from the university administration. Using a case study, students analyze the economics of running a university nanotechnology research laboratory. The exercise accorded students the opportunity to collect data related to the cost of research-enabling laboratory items, the capital outlay of the major fabrication and characterization equipment, and the operational cost of such a facility. The research seminars augment the hands-on portion and aforementioned courses; they are given by scientists and engineers who use the various tools and techniques in specific fundamental and applied research projects. Examples of seminars include “New Insights into the Microdomains within Heart Cells” and “2D Material Nanophotonics for Optical Information Science.”

During the summer, the fellows conduct a research project in which they specialize in fabrication or characterization. The projects focus on one tool/technique, so students develop more advanced skill beyond the learning in the units. The first cohort conducted the following projects:

1. Towards a Smart Contact Lens: Design and Fabrication of an RF Antenna on a Flexible Substrate
2. Silicon-Photonics: Fabrication of a Low-loss Grating Coupler and Waveguide
3. Energy Materials Analysis for Additive Manufacturing by Selective Laser Melting
4. Electrically Conductive Materials Analysis for Additive Manufacturing by Inkjet Printing

Each project group is paired with an advisor who is a professor with the requisite expertise. The fellows meet at least once a week with the advisor and a graduate student mentor. Throughout the program, the fellows hold journal clubs in which they analyze nanotechnology research articles. They are taught a reading comprehension technique (KWL – know, want to know, learned) which they apply during the journal club. The project culminates in a final presentation to peers, professors, research scientists, lab managers, and graduate students. Prior to the presentation, students participate in a workshop on how to give a good technical presentation, and they conduct practice sessions in which they receive feedback from peers and subject area experts. During the academic year, students present the research project at the poster session of the SEAS Research and Development Showcase.

During the academic year, fellows conduct two long-term projects. In one project designed to develop nanofabrication and characterization expertise, students become “super-users” on specific tools/equipment. They learn in-depth about their chosen tool and develop summaries and descriptions which communicate the tool’s uses and features to the broader community. The fellows become the in-house tool experts and develop training materials and sessions to train other users. They work closely with research scientists, facility managers, and vendors through the project. The second project is a research project similar to the summer session project. Students get extensive experience applying nanotechnology tools and techniques to a research project.

Community outreach

The fellows present their projects to their peers, university faculty and staff, and the DC community. For instance, the fellows selected one group to present its microfluidics project to the science department at a Washington, DC multicultural high school. The science teachers were enthusiastic about the project, and have brainstormed ways to integrate it into their curricula. The high school teachers indicated exposure to STEM ideas and activities is most important for their students. Exposure to the nano/micro-technology projects and the undergraduate students conducting them would strongly motivate the high school students to go to college and pursue STEM fields. In Fall 2015, the fellows held a nanotechnology workshop in which they explained fabrication and characterization techniques to a group of local high school students and teachers. In Spring 2016, the fellows presented their research projects at the School of Engineering and Applied Science Research and Development Showcase; it is an event attended by peers, faculty, staff, administrators, alumni, and members of the community.

Evaluation Results

The evaluation goal is to determine the impact of the program on fellows' choice of major, career interest, and confidence in their nanotechnology skills. The evaluations and focus groups are designed and conducted by researchers in the university's Office of Academic Planning and Assessment. The program outcomes are measured by course and program evaluations, focus groups, and project portfolios. The evaluations and focus group protocols inquire about students' interests, how such interests have evolved over the course of the semester and school year, and how the program has impacted their future career considerations. The portfolios are works-in-progress. Nanofabrication and characterization experts (in-house research scientists and professors) have commented on the projects' effective use of nanotechnology tools and processes. A formal evaluation of the portfolios is slated for the end of the academic year.

In the results to date, students have expressed fascination with the nanotechnology fabrication and characterization tools. They value the learning and experience both specifically in nanotechnology and broadly in cutting-edge technologies and research. Focus groups and course evaluations demonstrated students have developed confidence in using the cleanroom and microscopy tools on their own. For example, course evaluations showed that respondents expressed they were either very confident or somewhat confident in their skills and knowledge of nanotechnology. Also, a majority of evaluation respondents reported that they understand and can analyze examples of devices and emerging technologies enabled by specific nanofabrication techniques and/or physical phenomena at the nanoscale. The fellows program participants particularly value the hands-on experience with the tools and the exposure to research as exemplified by one response:

> I feel like I have learned a lot each day about things that I otherwise would have never been exposed to. The best part of the program, I think, is the amount of hands-on training that we have received. Having this type of experience so early in our college careers creates a safe environment for us to figure out which types of research we are most interested in-- or if we are interested in research at all. This does not only apply to nanotechnology research, either. We are being taught processes and questions which would need to be accounted for in any type of research. Having this so early on gives us the opportunity to explore all options without becoming restrained to only this career path, and many of the skills we have learned, such as presentation skills and reading journal articles, will be applicable no matter what we choose to do after graduation.

This response is also representative of a key result. In spite of having a positive experience, students are still uncertain about whether they want to pursue a career in nanotechnology. This uncertainty occurs mostly with the students who were rising sophomores during the summer session; these students want to continue to explore their educational opportunities. The desire was very pronounced when 50% of the 2015 summer session fellows chose not to continue with the program in order to study abroad during the academic year. (The SEAS student affairs office reported a record number of students electing to do study abroad this year.) Two students elected to pursue interests in other topics (robotics and aerospace vehicles). On the other hand, one student felt the fellows program provided such a unique opportunity that she decided to forgo a study abroad program in order to stay in the Nanotechnology Fellows Program. The program seems to have more traction with juniors. All of the juniors expressed an interest in staying with the program; one was not able to do so due to a heavy course load. The remaining juniors express strong interest in continuing in nanotechnology fields and careers.

The evaluation and focus group results indicate the efficacy of the scaffolding and hands-on training approaches. While the approaches affect learning of nanotechnology topics, they also seem to affect the students' development of identity as a budding engineer or scientist. The evolution from passive student to active and engaged professional was captured by one fellow:

> This program has escalated my understanding of what it takes to be an engineer… in such a short time I went from reading textbooks and sitting in large lectures to working in a lab and learning the basics of upper-level courses… I'm analyzing recent research articles and then instantly applying that knowledge…I like how we aren't treated like sophomores in undergrad but as capable researchers and colleagues. There is a nice balance between realizing that we are students early in our undergraduate career, in the mini-lectures, and fully capable colleagues in the EBL training or researcher seminars… this program provides a hands-on and personal experience unlike a lot of other opportunities. I like that were running our own projects yet we have a professor or graduate student to refer to.

There may be a need for more scaffolding related to experiment and research methodology. The students' lack of experience led to apprehension and anxiety during the research project in spite of the advising and mentoring resources as expressed by multiple fellows' reflections:

> …my least favorite part of the program has been the large project, which I only dislike because it is a different type of learning than I'm used to. Even though it is difficult, I appreciate that I'm being pushed outside of my comfort zone. I would change the process just a little to be more structured at the beginning and have a place with examples of how and [*sic*] experiment should be planned and run.

> It was challenging because we had to trouble-shoot on our own, we had to figure out how fix the issues on our own, and I think that was the most challenging. This is not like anything we have experienced in any of our classes. Usually if there is a problem, somebody tells you how to fix it. Here we had to figure things out on our own.

These sentiments may be due to the students' underclassmen status or the uncertain nature of research. Students have not taken core, upper level science and engineering courses, and research projects are unlike classroom/laboratory activities with predetermined methods and results. However, the challenge of open-ended projects could lead to independence and the very skills and capability which are the goal of the program.

Another primary goal of the Nanotechnology Fellow's Program is to foster an interest in nanotechnology, or engineering more broadly, as a potential career path for young scholars. Following the summer program, a majority of the fellows indicated in a focus group that they would look forward to learning about how nanotechnology can be applied to different careers in the engineering field. A majority of these students also indicated plans for pursuing a graduate degree in engineering. Course evaluation responses reflected similar findings:

> The way nanotechnology concepts were presented to me in this course got me very interested in nanotechnology. I learned so much about different applications and uses of nanotechnology and this has motivated me to begin thinking about how I could apply nanotechnology principles to my career. I would love to begin working as an intern or research assistant to aid in understanding nanotechnology better. I recommend this set of courses to many people I know who enjoy engineering…

Overall, using different methods of evaluations, it is clear the Nanotechnology Fellows Program is having a positive impact on students. The students appreciate the hands-on experience offered through the program, as well as the opportunities to conduct their own research. Furthermore, results demonstrate interest in learning more about nanotechnology, engineering and different career opportunities within the field.

Conclusion

The Nanotechnology Fellows Program and corresponding courses are expected to prepare students to enter the workforce and invent and implement next-generation technologies. The program has technological impact through the development of novel implementations of nanotechnology-relevant research projects which engage diverse groups of students, and these activities foster interdisciplinary collaboration of students and faculty. The program's use of scaffolding and integration of teaching and research have led to student interest and knowledge of nanotechnology topics, development of skills and experiences for careers in cutting-edge fields, and enthusiasm for science and engineering tools, advancements, and research. The evaluation results demonstrate this fellows program structure and approach could be effective in other cutting-edge fields as well.

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