Nanotechnology Fellows Program: An Interdisciplinary Practicum for Nanotechnology Undergraduate Education

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In spite of a significant need for science and engineering students to enter the workforce with skills in cutting-edge topics and technologies, there is limited opportunity to achieve the relevant skills and experiences at the undergraduate level. An undergraduate nanotechnology fellows program has been designed and implemented to extend beyond typical introductory course material and lab activities and give students meaningful, hands-on experience in nanotechnology. The interdisciplinary program targets freshmen and sophomores at The George Washington University and includes students and professors from multiple departments. The program has summer and academic year components which include tutorials, hands-on training and activities, seminars, professional development and research skills workshops, research projects, and presentations to the university and local high school communities. The topics are within the three themes: fabrication, characterization, and finance. The program utilizes a unique teaching-dedicated nanotechnology laboratory. Evaluation and focus group results demonstrate the efficacy of implementing nanotechnology education at the underclassmen level, the impact of integrating research and teaching, and the capacity of underclassmen to synthesize their academic and professional development as a result of their participation in the program.
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Introduction

From microscopy to materials synthesis, the demand for expertise in nanotechnology spans multiple disciplines and encompasses a variety of careers. The requisite education and training typically occur at the graduate level which limits undergraduates’ access to cutting-edge jobs and many companies’ workforce options. 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 only senior year only. Closely related to the demand for expertise is the knowledge required to initiate the innovation to venture process. 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.

The prolific presence of nanotechnology throughout society necessitates an educated workforce which can address the technological, societal, economic, and policy issues the emerging technologies present. Emerging technologies are leading to the development of many new opportunities to guide and enhance learning. This program links nanotechnology classroom education with practical, real-world nanotechnology applications and issues in industry, government, and academia. Educators face challenges in the design of a nanotechnology course that appeals to not only engineering students, but non-engineering students as well. Pedagogical approaches involving collaborative group learning, interdisciplinary learning, problem-based learning, and peer assessment are successful across a wide range of disciplines. The program and corresponding courses use these approaches to provide students with a background in the vernacular, fundamental physics, techniques and tools, and economic and policy issues in nanotechnology. A sequence of nanotechnology courses allows students to apply cutting-edge nanotechnology research findings to their core curricula coursework. This is a particularly important interdisciplinary breakthrough since currently there is little connection to the economic and policy factors involved in nanotechnology research and development at The George Washington University even though GWU has clear strengths in business and policy research.
Experiential learning opportunities are particularly effective for developing understanding, accessing higher order cognitive skills, and generating student interest\textsuperscript{11–13} which motivates the practicum approach represented by the Nanotechnology Fellows Program. The fellows program provides a practicum experience for students to get hands-on training with nano-fabrication and characterization equipment. This program and coursework gives students the opportunity to apply their learning, gain additional insights and expertise, and observe nanotechnology in action. These combined experiences will create a workforce of engineering graduates with interest, expertise, and experience in nanotechnology. It will enable graduates to be competitive in leading industries such as semiconductor manufacturing, renewable and sustainable energy, and biotechnology.

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 highly 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 systems and management engineering.

The program targets freshmen and sophomores to influence students early in their academic careers, establish program longevity, and enable scaffolded 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 School of Engineering and Applied Science (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. Implementing a GPA requirement could limit the diversity of the cohort; 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. The composition of the 2015 cohort is provided in the table below.

Table 1: Composition of the Nanotechnology Fellows Program cohorts. The 2016 cohort projections are provided in parentheses; the cohort will be finalized in May 2016.

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<td>Female</td>
<td>2 (1)</td>
<td>2 (1)</td>
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<td>Male</td>
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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 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 units on fabrication, characterization, and monetization. The units include theory and examples of applications. Each unit 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 summer session of the Nanotechnology Fellows 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 graduate student mentors. The program uses the university’s nanotechnology teaching laboratory which is designated exclusively for student teaching and training purposes. 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
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 feedback from the high school teachers was exposure to these 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 program outcomes are measured by course and program evaluations, focus groups, and project portfolios. 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. The evaluations and focus groups are designed and conducted by researchers in the university’s Office of Academic Planning and Assessment. The evaluation questions are:

- As a result of the program, have undergraduate Fellows from various disciplines developed expertise in nano-fabrication and characterization tools?
- To what extent has the program effectively integrated nanotechnology concepts across core disciplinary curriculum courses?
- Have the program’s outreach and dissemination strategies effectively brokered nanotechnology to 6-12 grade teachers and students across the DC metro area?
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. 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.

In the middle of the academic year following the 2015 summer program, a follow-up evaluation was conducted to determine the influence of the program on students' interests and professional pursuits. Table 2 summarizes responses that were quantified on a Likert scale. Interestingly, one student indicated the program influenced him/her to change his/her major to chemical engineering. Students were also asked about their plans for Summer 2016. Three students will be doing research internships on projects related to nanotechnology at the Naval Research Lab and National Institute of Standards and Technology. One student will be mentoring the 2016 Nanotechnology Fellows Program cohort and conducting undergraduate research in nanotechnology at a university lab. Two students indicated they are not interested in pursuing nanotechnology, and they will do internships in other fields (aerospace engineering and signal processing). One student will participate in a study abroad program.
Table 2: Follow-up evaluation questions posed to Nanotechnology Fellows Program cohort one semester after participation in the summer program.

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<th>Evaluation question</th>
<th>Average Likert scale score</th>
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<tr>
<td>Rate your overall satisfaction with the Nanotechnology Fellows Program</td>
<td>3.9</td>
</tr>
<tr>
<td>To what extent have the skills you learned in the program been applicable in your studies this year?</td>
<td>3.4</td>
</tr>
<tr>
<td>As a result of this program, how interested in your in exploring internships or summer opportunities in the field?</td>
<td>3.7</td>
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The evaluation results have led to modifications to the program structure for Summer 2016. One of the 2015 Fellows will serve as a mentor for the 2016 program to provide more intimate support for the students both in learning the material and pursuing the research endeavors. The research project will be implemented with more structure including project timelines and more frequent assessments of student progress. Outreach activities with the high school partner will occur early in the program allowing students to recognize the expertise they are gaining early in the program.

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.


Biographical information

Saniya LeBlanc is an assistant professor in the Department of Mechanical and Aerospace Engineering. Dr. LeBlanc's research goals are to utilize nano- and micro-structuring techniques to improve energy systems and create techno-economic models for emerging energy technologies. She obtained MS and PhD degrees from Stanford University, an MPhil from Cambridge University, a BS from Georgia Institute of Technology, and a teaching certification from American University. She served in Teach For America as a high school math and physics teacher and was co-founder of the ASEE Stanford chapter.

Volker J. Sorger is an assistant professor in the Department of Electrical and Computer Engineering, and the director of the Nanophotonics Labs at The George Washington University. He received his PhD from the University of California Berkeley. His research areas include opto-electronic devices, plasmonics and nanophotonics, including novel materials. Dr. Sorger is the executive chair of the OSA Nanophotonics technical group, editor-in-chief for ‘Nanophotonics’, CTO of BitGrid LLC, and member of IEEE, OSA, SPIE, and MRS.

Ekundayo (Dayo) Shittu is an assistant professor in the Department of Engineering Management and Systems Engineering, and the director of Climate Change, Energy and Economic Decision Modeling Laboratory. He received his Ph.D. from the University of Massachusetts Amherst. His research focuses on decision making under multiple and sequential uncertainties in the economics and management of energy technologies and in the design of climate change response policies. Central to his research is the development of appropriate policies to encourage commercialization of, and investments into, emerging technologies.