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Undergraduate Research and Education in Nanotechnology*

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In this paper, we discuss the development, implementation and evaluation of a 'Research Experiences for Undergraduates' program in nanomaterials processing and characterization offered at the University of Central Florida. Here, we focus in particular on details pertaining to the program's instructional design and subsequent evaluation that may be useful for other engineering educators involved in undergraduate research and education in nanotechnology. Based on our analysis of program outcomes, implications are suggested for undergraduate and postgraduate engineering education programs that focus on aspects of nanoscale science and technology.

Keywords: nanotechnology; undergraduate research

INTRODUCTION

IN 2001, THE National Nanotechnology Initiative [1] was launched in the USA, after having being approved by the US Congress in November 2000 and funded for a total of $422 million for the 2001 fiscal year [2]. By the 2004 fiscal year, federal funding for the NNI had more than doubled, to approximately $961 million (additional budget details for the US National Nanotechnology Initiative may be accessed at http://www.nano.gov/html/about/funding.html) [3]. This initiative and similar initiatives worldwide (e.g. in Australia, Canada, China, Europe, India and Japan) have led to calls within the scientific community for concerted efforts to educate not only future scientists and engineers, but also the general public regarding ongoing developments in nanoscale science and technology [4, 5].

Several key recommendations have been offered by the US National Science Foundation [2] to address the education and training of future scientists and engineers in nanoscale science and technology. These include the development of specific curricula and educational programs to 'introduce nanoscale concepts into mathematics, science, engineering, and technological education; include societal implications and ethical sensitivity in the training of nanotechnologists; develop effective means for giving nanotechnology students an interdisciplinary perspective while strengthening the disciplinary expertise they will need to make maximum professional contributions; and to establish fruitful partnerships between industry and educational institutions to provide nanotechnology students adequate experience with nanoscale fabrication, manipulation, and characterization techniques' (pp. iii–iv). The highly interdisciplinary nature of nanoscale science and technology research (and the desire to accelerate advancements in these areas) has led to a number of efforts at university level that integrate various lines of research and corresponding education efforts.

The NSF Research Experiences for Undergraduates program

The National Science Foundation's Research Experiences for Undergraduates (REU) program [6] is an important component of the organization's mandate to improve the quality of science, technology, engineering and mathematics (STEM) education in the US. The REU program specifically targets academically able students in these disciplines, and provides resources that allow these students to participate in undertaking original research rather than only learning about the research and research findings of others. The focus of the program on exposing undergraduate students to research aligns with national goals to produce a greater number of well-prepared STEM professionals [7] who eventually will contribute to the advance of knowledge in various STEM disciplines (academia/industry) and STEM education. The focus of the REU program also complements a major recommendation of the National Nanotechnology Initiative [1]; i.e. that exposure to various areas of research in nanoscale science and technology ought to occur at the undergraduate level, so that these students begin to develop the requisite interdisciplinary knowledge, skills and perspectives for successful future research and education in the field.

Here, we report one such initiative at the University of Central Florida (UCF) that received funding from the National Science Foundation's REU program (Division of Engineering Education and Centers) to establish an REU site in Nanomaterials Processing and Characterization

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(NANOPAC-REU). Initial funding was received for support of a three-year effort, beginning in the summer 2002 semester. In the sections below, we present: a general description of the NANOPAC-REU program; selected 'highlights' of the program; details of the program evaluation; discussion of current issues and concerns in nanoscale science and engineering education; and concluding comments.

THE NANOPAC-REU SUMMER PROGRAM AT UCF: AN OVERVIEW

Program logistics and demographic data

The NANOPAC-REU program at UCF was designed as a series of 10-week experiences occurring in the summer semesters (i.e. mid-May to the end of July) of 2002, 2003 and 2004, respectively. The primary goal of the respective 10-week experiences was to provide eligible undergraduate students with opportunities to become actively involved with participating faculty mentors' research groups and research projects in nanoscale science and technology being undertaken at the University. Complementary goals of the program are discussed in the program evaluation section below. The program was administered via the Advanced Materials Processing & Analysis Center (AMPAC) affiliated with the UCF College of Engineering & Computer Science. For each of the three initial summer programs, 10 high academically performing science and engineering undergraduate students were selected from institutions across the US to participate in intensive research experiences on a wide range of nanomaterials topics, including: processing of nanostructured materials; processing and characterization of carbon nanomaterials; nanostructured polymeric materials; applications (e.g. sensors, optics, coatings, thin films); nanospectroscopy using lasers; and high-resolution transmission electron microscopy [8].

During the final selection process, efforts were made to address adequate diversity among the students in terms of sex and ethnicity. These and other demographic details are provided in Table 1.

While it is encouraging that women comprised fully one-third of the 30 students participating in the program over a three-year period, the ratio of men to women nevertheless continues to support the well-documented trend that science and engineering are still male-dominated fields [9–11]. Also, it is noted that no African-American students participated in the program over the initial three-year period. Despite documented increases of African-Americans pursuing undergraduate degrees in science and engineering, they and other minority groups continue to be underrepresented in these fields [9, 10, 12].

Several students were enrolled in 'double majors' (two undergraduate degrees being taken simultaneously), e.g. Physics/Astrophysics.

Institutions represented

BYU	Brigham Young University (Utah)
Cooper	Cooper Union (New York)
CPSU	California Polytechnic State University–San Luis Obispo
FIT	Florida Institute of Technology
FIU	Florida International University
Lafayette	Lafayette College (Pennsylvania)
NJIT	New Jersey Institute of Technology

Table 1. Demographics of NANOPAC-REU student participants, summer 2002 to summer 2004

Year	Sex and ethnicity[†]		Undergraduate degrees being pursued[††]	Institutions represented[†††]
Summer 2002	Female (3): 1 Asian, 2 White	Male (7): 1 Hispanic, 6 White	* Biochemistry * Electrical Engineering * Materials Science & Engineering * Mechanical Engineering * Mechanical Engineering/Physics * Microbiology/Immunology * Physics/Astrophysics	BYU, NJIT, NYU, UCF, UF, UM, UMR
Summer 2003	Female (2): 1 Asian, 1 Hispanic	Male (8): 1 Asian, 7 White	* Chemical Engineering * Computer Engineering & Applied Mathematics * Electrical Engineering * Materials Engineering * Mechanical Engineering * Molecular & Microbiology * Physics	BYU, CPSU, FIT, FIU, Lafayette, NJIT, UCF, UF
Summer 2004	Female (5): 1 Asian, 2 Hispanic, 2 White	Male (5): 1 Asian, 1 Hispanic, 3 White	* Bioengineering * Biomedical Engineering * Electrical Engineering * Chemical Engineering * Electrical/Computer Engineering * Materials Engineering * Mechanical Engineering * Molecular and Integrative Physiology & Chemistry	Cooper, FIU, UC-Berkeley, UCF, UCT-Storrs, UF, UIUC, UMN-Duluth, UR

NYU	New York University
UC-Berkeley	University of California-Berkeley
UCF	University of Central Florida
UCT-Storrs	University of Connecticut-Storrs
UF	University of Florida
UIUC	University of Illinois at Urbana-Champaign
UM	University of Memphis (Tennessee)
UMN-Duluth	University of Minnesota-Duluth
UMR	University of Missouri-Rolla
UR	University of Rochester (New York)

Guiding philosophy and program structure

The educational philosophy that was employed to guide the structure and subsequent operational development of the NANOPAC-REU program may best be described as 'situated cognition'. In essence, situated cognition—a theory that seeks to explain how humans learn most optimally—suggests that learning is primarily a process of enculturation. The acquisition of meaningful knowledge is situated in some activity and sense is made of that knowledge within specific contexts and cultures [13]. As an epistemological theory, proponents of situation cognition argue that membership in a particular culture and the use of 'tools' (physical or conceptual) idiosyncratic to that culture act together to determine the way practitioners within the culture see the world. To learn to use tools as practitioners use them, a student, like an apprentice, must to some extent enter that community and its culture. Thus, in a significant way, learning becomes a process of enculturation; i.e. the facilitated entry of an individual into a specific culture [13–17]. In this sense, the primary goal of the NANOPAC-REU program (exposure of undergraduate students to various areas of research and education in nanoscale science and technology in an intensive 10-week experience) may be regarded as a deliberate effort to introduce students to the developing culture of nanoscale science and technology by having them become conversant with its fundamental tenets, defining concepts, theories and laws, specific modes of communication, and accepted methods of knowledge generation and validation.

Congruent with the educational philosophy of 'situated cognition' are the instructional approaches of 'problem-based' and 'project-based' learning. Ditcher's [18] discussion of effective teaching and learning approaches in the undergraduate education of professional engineers describes the advantages offered by problem-based learning in engineering education. This instructional approach is characterized by students first defining a problem, then identifying and acquiring the skills and knowledge to solve the problem, and subsequently working collaboratively to satisfactorily solve the problem (p. 27). Such an approach serves as one example of a 'deep' versus a 'surface' approach to learning [18, 19]. While some aspects of the NANOPAC-REU program reflected a problem-based approach (e.g. working in collaboration with a faculty mentor; see below), participating undergraduate students were not solely responsible for defining and then selecting a particular research problem or area of inquiry. A project-based learning approach more suitably describes the *modus operandi* of the program. As indicated by Mills and Treagust [20], the term 'project' is universally used in engineering practice to mean a 'unit of work'. Different projects vary in complexity, but all relate in some way to the fundamental theories and techniques of an engineer's discipline specialization (p. 8).

The decision to adopt a predominantly project-based approach rather than a predominantly problem-based approach in the NANOPAC-REU program is appropriately supported by Perrenet *et al.*'s [21] analysis of the primary differences between the two approaches: i.e. project tasks are closer to the professional reality of engineering and therefore (typically) take a longer period of time than activities using a problem-based approach; project work is more directed to the application of knowledge, whereas problem-based learning is more directed to the acquisition of knowledge; project-based learning is usually accompanied by supporting subject area courses, whereas problem-based learning is not; management of time and resources by the students as well as task and role differentiation is very important in project-based learning; and self-direction is stronger in project work, compared with problem-based learning, since the learning process is less directed by the problem (p. 348).

In keeping with the guiding educational philosophy of 'situated cognition' and the complementary instructional approach of project-based learning, each undergraduate student was paired with a UCF faculty member pursuing a research program involving some aspect of nanomaterials processing, characterization or applications development. Additionally, undergraduate students also interacted extensively with postgraduate research assistants working on various research projects with the designated faculty mentors. Representative examples of ongoing research projects in which the students participated are given in Table 2.

Reflecting the interdisciplinary nature of research in nanoscale science and technology, participating UCF faculty research mentors were drawn from the fields of engineering, materials science, physics, chemistry, optics and molecular biology/microbiology. In addition, students were involved in extensive complementary educational activities, including a weekly seminar series focusing on their research projects, career development seminars, presentations by nanotechnology research and development guest speakers (e.g. US Filter; Nanopowder Enterprises; PsiloQuest), and field trips to local industries, research centers and laboratories involved in nanotechnology

Table 2. Examples of specific NANOPAC-REU research projects

Year	NANOPAC-REU research projects (selected examples)
Summer 2002	* Synthesis and characterization of nanocrystalline alumina and Ni-coated alumina * Nanoscale characterization with high resolution transmission electron microscopy of vanadium implanted in silicon * Nanocrystal formation in ball-milled materials * Development of direct laser deposited thermal barrier coatings from micro- and nano-sized powders
Summer 2003	* Nanocomposites: Increasing stress factors of nano-phased ceramic reinforced metal composites * Nanopolymers: Utilizing iron nanoparticles to manufacture magnetic polymers * Nanomechanics: Nanoindentation of shape memory alloys * Nanocoatings: Tensile analysis of polymers bonded with carbon nanotubes * Nanotubes: Use of peptides to separate nanotubes
Summer 2004	* Solgel-derived metallic and oxide nanomaterials for thermal, optical and sensor applications * Processing and characterization of carbon nanomaterials * Discontinuously reinforced nano-aluminum composites * Focused ion beam applications in nanotechnology * Nanostructured biomaterials * Microsensors using nanostructured materials * Performance of solid rocket propellants with nanoparticle additives

development (e.g. Lockheed Martin; Argonide Corporation). Specialized seminars on 'social and ethical issues in nanoscale science and technology' and 'intellectual property protection and technology commercialization' also were presented by participating faculty. As a capstone to their REU experience, each student was required to prepare and give a research presentation at a concluding poster session to UCF faculty, administrators and invited industry participants.

A variety of complementary seminars was offered throughout the summer programs, typically beginning at 10.00 a.m. and conducted for a period of 1 to 1.5 hours. These are discussed in more detail in the section below. All students attended the respective seminars as a group. Following the seminars, the rest of the day—typically until 6.00 p.m. or later, as needed—was allocated to research in the laboratories of the respective faculty mentors. On days when no seminars were held, students were expected to be in their respective research laboratories for the entire day as needed. In addition to the various seminar offerings and the focus on active engagement in research, adequate time was allocated in the respective program schedules for social and other informal group activities. These included a student/faculty picnic and day trips to local attractions in the central Florida region (such as the National Aeronautical Space Agency/Kennedy Space Center).

Program highlights

Here we focus on specific components of the NANOPAC-REU program that are particularly relevant to engineering education in the context of exposing undergraduates to research in nanoscale science and technology. As we discuss below, the various seminars were designed to assist students to 'make the conceptual connections' from their individual research projects to other areas of knowledge, concerns and issues associated with nanoscale science and technology research, and served as an important process for the 'enculturation' of these students as potential future researchers and educators in the field. Five distinct but interrelated types of seminars were offered in the NANOPAC-REU program, each of which is briefly discussed in turn.

Research update seminars. These were held every other week during the respective summer programs, in which students were required to provide updates on the progress of their individual research projects. During these meetings, students gave short oral presentations to their peers and also to the NANOPAC-REU program director (the third author of this paper) concerning the status of their research. The research update seminars also served as a venue for bringing any pertinent administrative problems to the attention of the program director. Most importantly, these seminars allowed students to practice giving public presentations of their ongoing research, where they could discuss issues associated with their research (e.g. procedures, data analysis, preliminary findings, methodological problems) and subsequently receive feedback from peers in their respective groups. Similar in concept to a professional 'mini-conference' or colloquium, the research update seminars provided an opportunity for students to share information, ideas and concepts common to their individual projects, and also allowed them to collaboratively learn from each other [22, 23].

Specialized seminars from participating faculty. These seminars were held on a weekly basis throughout the summer programs and were presented by faculty mentors of individual NANOPAC-REU students. The specialized seminars provided an opportunity for participating faculty to present and discuss specific areas of their research with the entire group of students, and also provided students with a collective opportunity to be exposed to various areas of research in nanoscale science and technology being undertaken at UCF. This process enabled students to interact with and learn from experts in various areas of 'cutting edge' nanoscale science and technology research and, as in the research update seminars, the specialized seminars provided a forum where information, ideas and concepts common to their individual research projects could be shared. Topics of these specialized seminars included, for example, presentations on nanobiotechnology, nanocomposites and combustion of nanomaterials.

Guest seminars from business/industry and governmental representatives. Utilizing the professional contacts of UCF faculty and the NANOPAC-REU program director, representatives from several companies and research organizations (either devoted exclusively to research and development in some aspect of nanoscale science and technology or which were incorporating nanotechnology into existing research and development programs) were invited to participate in the NANOPAC-REU program as guest speakers. Two to three guest seminar presentations were offered each year. Over the period summer 2002–summer 2004, these included presentations given by representatives from, for example, US Filter (www.usfilter.com), Nanopowder Enterprises (www.nanopowderenterprises.com), AppliCote Associates (www.applicote.com), Lockheed Martin (www.lockheedmartin.com), PsiloQuest (www.psiloquest.com), National Aeronautics and Space Administration (www.nasa.gov) and the US Office of Naval Research (www.onr.navy.mil). These seminars provided students with insights regarding career opportunities available to them in nanoscale science and engineering research, and business/industrial applications following undergraduate or more advanced research and study. The guest seminars also played an important role in demonstrating to students how contemporary careers in academic science and engineering research typically interact with and are influenced by business/industry and governmental agencies—i.e. the 'triple helix' of academia–industry–government relations to which Etzkowitz and Leydesdorff [24] refer. These and related topics were further explored in the seminars addressing 'research patenting and commercialization' and 'social and ethical issues in nanoscale science and technology research'.

Seminars on research patenting and commercialization. One seminar per summer program was held on 'research patenting and commercialization', presented by the second author. In these seminars, topics presented and discussed with the students included: an overview of intellectual property and technology transfer procedures at UCF [25]; the patenting process and why many research universities now seek to patent and/or license discoveries and inventions; generation of university revenue from patenting and licensing; trademarks, copyrights and trade secrets; and researcher/university responsibilities and obligations in matters of patenting, licensing and the commercial use of intellectual property. A brief presentation also was made regarding the UCF Technology Incubator, whose stated mission is that of being 'a University-driven community partnership providing early stage technology companies with the enabling tools, training and infrastructure to create financially stable high growth enterprises' [26].

As part of the NANOPAC-REU program, students were made aware of the rapidly increasing number of nanomaterials processing, characterization and applications patents held at UCF and other US research universities, which provided an immediate context for the purposes of these seminars. Recent commentators such as Mazzola [27] and Paull *et al.* [28] note that, while commercial nanotechnology is still in its infancy and will require a concerted and sustained effort to convert basic science research discoveries into mass marketable products, the rate of technology enablement is increasing. Given that research in nanoscale science and technology is now integral to corporate research and development across a wide range of industries, business models within the 'triple helix' of academia–industry–government relations [24] will need to evolve and change because of nanotechnology's anticipated impact in the marketplace and wider global economy.

Seminars on emergent social and ethical issues in nanoscale science and technology research. Five seminars per summer program on 'social and ethical issues' were developed and presented by the first author. The seminars were discussion based, and emphasized active participation and debate (and, on occasion, spirited argument) between the REU students. Students first were introduced to definitions of 'ethics in engineering', using Martin and Schinzinger [29] and Spier [30] as primary source materials. Students then were asked to review and discuss selected professional engineering ethical standards from a variety of professional engineering organizations, including: the Accreditation Board for Engineering and Technology (www.abet.org); the Institute of Electrical and Electronics Engineers (www.ieee.org); the National Society of Professional Engineers (www.nspe.org); and the American Society for Engineering Education (www.asee.org). Although the background for subsequent discussions in 'nanoscience/nanotechnology ethics' was based on an initial review of professional standards and ethics pertinent to engineering, the material was presented in sufficient breadth so that the topics discussed were applicable across general science and engineering fields. Initial 'general science/engineering ethics' topics included the following:

- Objectivity and subjectivity in science
- Value judgments in science (i.e. 'good', 'bad', 'right', 'wrong', etc.)
- Merits of 'basic' versus 'applied' research
- Fabrication/falsification of data
- Data selection/manipulation
- Plagiarism
- Conflict of interest
- Authorship issues

- Mentoring issues
- Abuse of the peer review process

While no formal presentation of classical philosophical ethics (e.g. Aristotle, Kant, Locke, Mill, etc.) or of contemporary theories of technology [31–35] was attempted in the seminars, these were utilized in the conceptual design of the seminars [36], and various points of view relating to these perspectives inevitably were raised and discussed. Spier's [30] synthesis of 'ethical systems' (pp. 73–77) was used to initiate discussions relating to current and anticipated developments in nanoscale science and resulting technological applications. Throughout the seminars, a science–technology–society (STS) approach was emphasized, which sought to have the students think critically and analytically about the impacts of nanoscale science and technology on society, and the influence that their current and future research might have on future intersections of science, technology and societal concerns [37, 38].

Specific social and ethical concerns in nanoscale science and technology were broached by reviewing popular commentators in the field, such as Richard Feynman [39], K. Eric Drexler [40, 41], Ray Kurzweil [42–44], Bill Joy [45] and Ralph Merkle [46]. Subsequent discussions of ethical and societal implications also explored: how advances in nanoscale science and technology might influence or affect national and global economics; environmental sustainability; the development of pharmaceuticals; human lifespan and quality of life; and education/workforce preparation. More philosophically oriented ethical questions that were explored included the following: intellectual property (who 'owns' this knowledge?); university/industry/government relationships (who funds what, and why? [24, 47]); and, informing the general public (and to what extent?).

As Mnyusiwalla, Daar and Singer [48] have suggested, advances in nanotechnology will be derailed if serious study of nanotechnology's ethical, environmental, economic, legal and social implications does not maintain pace with progress in the science (p. R9). This provides a significant impetus for continuing our efforts to expose future scientists and engineers to these issues.

ASSESSMENT AND EVALUATION OF THE NANOPAC-REU PROGRAM

Assessment and evaluation of what students have learned (and the extent to which that learning has occurred) occupy a central position in engineering education. In the United States, the Accreditation Board for Engineering and Technology (www.abet.org) is the primary professional engineering organization responsible for validating the educational efforts of nationally ranked undergraduate and postgraduate engineering degree programs. In order to secure ABET accreditation, engineering colleges, schools, departments and programs must demonstrate a continuous emphasis is on what is learned by students rather than on what is taught [49]. This emphasis, as described by the American Society for Engineering Education [50], is on 'outcomes assessment'—i.e. a focus on determining what program graduates know and are able to do. Such outputs often are difficult to define and measure, a challenge typical in educational research, assessment and evaluation [51]. Although a variety of technical definitions exist for the terms 'assessment' and 'evaluation' [52–55], here we employ the definitions offered by Olds and Miller [56], where 'assessment' refers to the collection and analysis of data and, subsequently, 'evaluation' refers to interpreting and reporting findings about the data.

Two survey instruments (one for participating faculty, and one for participating undergraduate students) were utilized to obtain primary quantitative and qualitative data for assessment of the NANOPAC-REU program. The faculty and student questionnaires, respectively, were modified versions of survey instruments originally developed by The Cooper Union and Drexel University as part of the National Science Foundation sponsored Gateway Engineering Education Coalition (see http://www.gatewaycoalition.org). The modified survey instruments are available from the authors upon request. Use of these surveys complemented the project-based learning approach adopted in the program, and also provided a mechanism to anonymously assess students' perceptions of how well they had learned and practiced 'core skills' (i.e. analytical ability, communication, creativity/problem-solving, lifelong learning, project management, research, systems thinking, teamwork) and 'technical skills' (i.e. mathematical analysis, science knowledge, rational/objective reasoning, performance justification, citation of professional literature, assessment of environmental impacts, assessment of ethical/social impacts, cost estimates, addressing questions and issues, suggestions for improvement) during their participation in the NANOPAC-REU program. Development of these skills represented the complementary goals of the program. Students also were requested to rate their responses to question items concerning the overall structure and design of the program. The student survey was administered at the mid-point and again at the end of each summer program for purposes of ongoing, formative evaluation. After completion of the respective summer programs, a follow-up questionnaire was sent via e-mail to students, designed to elicit more in-depth qualitative/narrative feedback regarding their research experiences. The corresponding survey for mentor faculty (also completed anonymously) was used to elicit their perceptions of the extent to which their participation in the program had assisted students to learn and practice the 'core' and 'technical' skills described above. Like the students, faculty also

Table 3. Mean ratings, standard deviations and confidence intervals (p = 0.05) for summer 2002–2004 summative student responses to selected survey items

Summer 2002–2004 students (N = 30)	Mean rating	Standard deviation	Confidence interval (95%)
Core skills			
Research procedures	4.03	0.76	3.75–4.32
Project management	3.93	1.01	3.55–4.31
Communication	3.77	1.01	3.39–4.14
Creativity/problem-solving	3.47	1.04	3.08–3.86
Technical skills			
Citation of pertinent research literature	3.77	1.01	3.39–4.14
Use of interdisciplinary science knowledge	3.73	0.83	3.42–4.04
Rational/objective reasoning in design	3.73	0.87	3.41–4.06
Assess ethical and social impacts of research design	3.03	1.16	2.60–3.47
Assess environmental impact of research design	2.63	1.10	2.22–3.04
Develop realistic cost estimate of research design	2.43	0.90	2.10–2.77
Overall satisfaction with NANOPAC REU program	3.93	0.94	3.58–4.29

were requested at the conclusion of each summer's research activities to provide written comments suggesting how the overall structure and design of the program could be improved. Selected findings from the aggregated quantitative and qualitative data collected over the initial three-year period of the program are presented and discussed below.

Program data analysis

Tables 3 and 4 provide a cumulative analysis of student and faculty ratings of the indicated items over the period summer 2002 to summer 2004. Items are rated 1–5, where 1 = not at all, 2 = to a limited extent, 3 = to a moderate extent, 4 = to a great extent and 5 = to a very great extent. The selected items are those that consistently received the highest ratings (i.e. 4 and 5) and lowest ratings (i.e. 3 and below) from participating students and faculty over the initial three years of the program. Standard deviations and confidence intervals ($p = 0.05$) are given in order to provide a sense of the distribution of ratings relative to the mean ratings. Ratings on the selected survey items (measuring students' perceptions of the degree to which their involvement in the NANOPAC-REU programs had enabled them to develop these specific core and technical skills) are presented from highest to lowest, according to aggregated mean scores. Faculty ratings on the same items (measuring participating faculty members' perceptions of the degree to which their involvement in the NANOPAC-REU programs had enabled students to develop these specific core and technical skills) are likewise presented. Cumulative item ratings are based on the responses of a total of 30 participating undergraduate students and 17 participating research mentor faculty. (Although 10 nanotechnology research faculty participated in each summer program as undergraduate research mentors, not all participated as mentors in all three program offerings, 2002–2004. Two faculty members participated in 2002 only; one in 2003 only; four in 2002 and 2003 only; one in 2002 and 2004 only; four in 2004 only; and five in all three program offerings, 2002–2004).

In terms of core skills, both students and faculty rated 'research procedures' most highly. Given the focus of the NANOPAC-REU program, this is not entirely unexpected. The core skill given the lowest mean rating by students was that of 'creativity/problem-solving', whereas faculty assigned the lowest core skill mean rating to 'project management'. It is interesting to note that, while the cumulative student mean rating for 'creativity/problem-solving' was the lowest of the core skills

Table 4. Mean ratings, standard deviations and confidence intervals (p = 0.05) for summer 2002–2004 summative faculty responses to selected survey items

Summer 2002–2004 faculty (N = 17)	Mean rating	Standard deviation	Confidence interval (95%)
Core skills			
Research procedures	4.62	0.86	4.29–4.95
Creativity/problem-solving	4.45	0.87	4.12–4.78
Communication	4.38	0.82	4.07–4.69
Project management	4.23	0.69	3.98–4.50
Technical skills			
Use of interdisciplinary science knowledge	4.48	0.57	4.26–4.70
Citation of pertinent research literature	4.45	0.69	4.19–4.71
Rational/objective reasoning in design	4.41	0.68	4.15–4.67
Assess environmental impact of research design	2.97	1.09	2.55–3.38
Assess ethical and social impacts of research design	2.86	1.19	2.41–3.31
Develop realistic cost estimate of research design	2.79	1.18	2.35–3.24

assessed, the rating also had the largest standard deviation (1.04). However, although the cumulative faculty mean rating for 'project management' was the lowest of the core skills assessed, its comparatively low standard deviation indicated a greater consistency of sentiment among participating faculty.

Review of the ratings in terms of technical skills shows a broader range of trends in student and faculty responses. While 'citation of pertinent research literature', 'use of interdisciplinary science knowledge' and 'rational/objective use of reasoning in research design' all were given the highest mean ratings by students and faculty, students were rather more conservative in their perceptions, as indicated by the corresponding standard deviations and calculated confidence intervals of the ratings. Technical skills of being able to 'assess ethical and social impacts of a research design', 'assess environmental impacts of a research design' and 'develop realistic cost estimate of a research design' all received the lowest ratings, both by students and faculty. While the skill of developing a realistic cost estimate of a research design received the lowest mean rating by both groups, 'assessing ethical and social impacts of a research design' yielded the largest standard deviation within each group, and therefore more imprecise confidence intervals.

Cumulatively, the 30 students participating over the initial three-year period rated their overall satisfaction with the NANOPAC-REU program as 3.93 (SD 0.94; 95% confidence interval of 3.58–4.29), with 63% (19/30) rating their overall satisfaction with the program as 'excellent' or 'very good'. While these data indicate a reasonable level of program success in achieving the stated goals, reference to other data is needed to more fully evaluate aspects of the program that worked well, and those aspects of the program that will need improvement in future offerings. To complement the quantitative data offered above, we also present other program outcomes below as a means of providing a comprehensive evaluation of the NANOPAC-REU program. These are organized as student presentations and publications, current status of 2002 and 2003 NANOPAC-REU participants, and a qualitative evaluation summary of the 2002–2004 NANOPAC-REU programs, compiled from comments submitted by participating research faculty and students.

Student presentations and publications

At the conclusion of the respective summer programs, all NANOPAC-REU students were required to prepare and give a poster presentation of their research to UCF faculty, administrators, and invited guests representing various local science, technology and engineering companies. The culminating poster session was designed as a capstone experience, in which students gave oral presentations regarding all aspects of the research projects in which they had participated. This involved students in answering questions about their respective research rationales and methodologies, data obtained, and explanation of results. The following 'Abstract' and accompanying figure (Fig. 1) provides a representative example of the material included in REU students' poster presentations of their research projects.

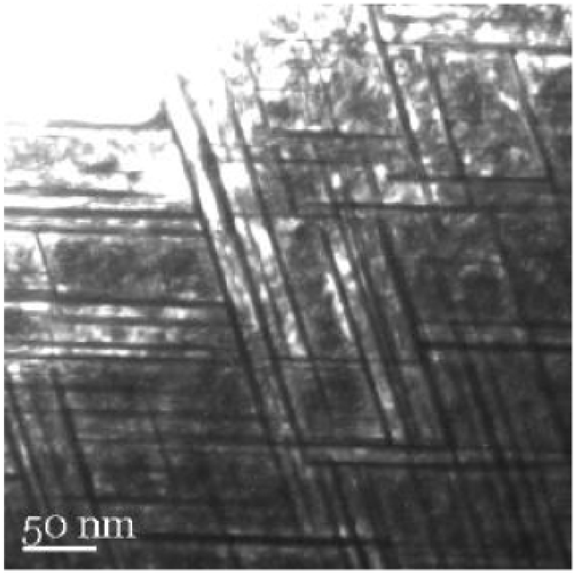

Fig. 1. 70-hour heat treatment at 140ºC: the first stages of the transformation from individual Ag_2Al plates to a parallel arrangement of these XX plates in a lamellar nanostructure are clearly revealed. TEM image obtained by REU 2004 student, Bradley E. Kabes (research mentor, Dr. Helge Heinrich, UCF Department of Physics/AMPAC). A complete list of all NANOPAC-REU student research projects, 2002–2004, may be viewed at http://www.nanoscience.ucf.edu/nanopac_ activitiesYearbook.html.

In addition to the required poster presentations for all NANOPAC-REU students, a small number of students also gave refereed presentations with UCF faculty research mentors at regional or national conferences, and co-authored refereed publications related to their REU research projects. While conference presentations and refereed publications co-authored with UCF faculty were greatly encouraged, we have primarily evaluated the NANOPAC-REU program by its educational value, as opposed to a focus on 'pushing' students to obtain publishable results; our view is that such a focus would very likely occur at the expense of the students' overall learning in the program. During the initial three years of the NANOPAC-REU program, students participated in eight research presentations at national level professional conferences (e.g. American Vacuum Society; Electrochemical Society; Materials Research Society; American Ceramics Society; Nature Biotechnology symposium; National Conference on Undergraduate Research). Over this period, students also co-authored five refereed journal or 'proceedings' research publications. Details of the publications in which REU students were involved are provided in the Appendix. Figure 2 provides an example of the manner in

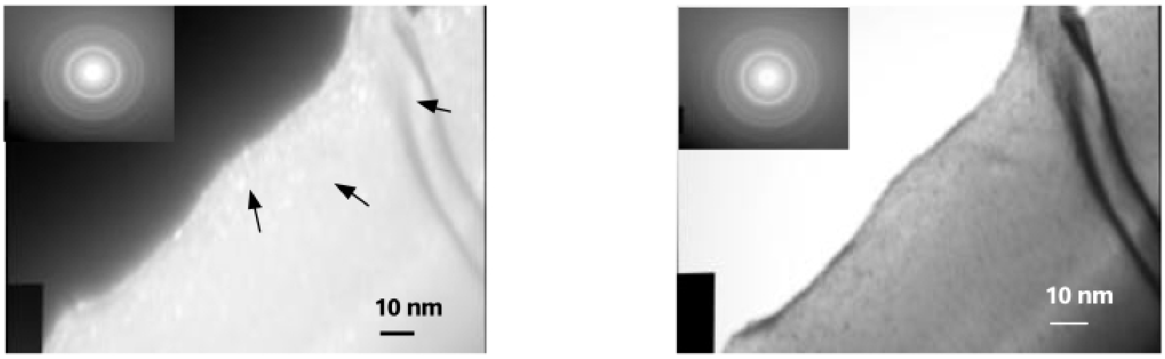

Fig. 2. Physical and optical properties of sol-gel nano-silver doped silica film on glass substrate as a function of heat-treatment temperature. TEM images obtained by REU 2002 student of SiO_2 gel containing 0.05% Ag, with inset diffraction patterns of Ag particles (see *Journal of Applied Physics*, **93** (2003), pp. 9553–9561).

which one REU student's research project was incorporated into a formal peer-reviewed publication.

Current status of 2002 and 2003 NANOPAC-REU participants

At the time of writing, the students participating in the summer 2004 NANOPAC-REU program all were still completing their undergraduate studies. We have endeavored to 'track' the short-term career trajectories of the summer 2002 and 2003 students, in an attempt to determine whether their participation in the program has had any influence on their subsequent professional activities.

Of the summer 2002 cohort, three students are pursuing Master's degrees specifically addressing some aspect of nanoscale science and technology research; two are employed in science and engineering-related industries; two are pursuing Master's programs not explicitly addressing nanoscale science and technology research (i.e. biology, law); one is in medical school; and there are no available data for two students. Of the summer 2003 cohort, three students are pursuing Master's degrees (or have been accepted into Master's programs) specifically addressing some aspect of nanoscale science and technology research; two are employed in science and engineering-related industries; three are pursuing Master's programs not explicitly addressing nanoscale science and technology research (i.e. health, biomechanics, polymers); one is in business school; and there are no available data for one student.

While it remains well beyond the scope of the available data to indicate a direct relationship between participation in the NANOPAC-REU program and subsequent professional activities, our preliminary analysis suggests that the NANOPAC-REU program has been successful in meeting the primary goal of encouraging students to pursue research careers. Besides the six students who are specifically pursuing some aspect of nanoscale science and technology research, those pursuing graduate studies in other areas and those now employed in various science and engineering-related industries are likely to encounter issues pertaining to research in nanoscale science and technology. We speculate that this will be true even for those students pursuing graduate studies in the fields of law and business, given the increasing attention now being paid to legal and commercial aspects of nanotechnology research [27, 28, 57].

Evaluation summary

As indicated in a recent report [58], 'in academic and research circles, it is widely believed that undergraduate research opportunities help encourage undergraduates to pursue research and teaching careers' (p. ES-1). We concur with this sentiment, and point to the data presented to support our conclusion that the initial three-year NANOPAC-REU program was successful in meeting its primary goal of effectively involving undergraduate students in nanoscale science and technology research. In so doing, the program serves as a useful example of 'activities envisioned for engineering education' that will be necessary to advance research and education in nanoscale science and technology [5].

According to Davidson [55], comments about the quality, effectiveness or value of an activity or program constitute an 'evaluation'. While it always is tempting for program developers/university faculty to report only the 'best' available data as evidence of successful program outcomes, we think it is important to demonstrate a level of objectivity and self-critique in order to improve the educational quality of future program offerings.

Analysis of student and faculty feedback (both written and oral) has provided insights into those factors that contributed to the operational successes, operational challenges, and overall educational value of the NANOPAC-REU program. Achievement of the program's complementary goals (i.e. the core and technical research skills indicated on the survey instrument) occurred to varying degrees, and it is clear that plans for future program offerings will need to carefully address at least four key issues. First, the selection of faculty and the careful matching of students with committed faculty appear to be two of the most influential factors governing the overall success of the program. Given the involvement of many UCF faculty in research often requiring national and international travel for extended periods (particularly during the summer months), this has, at times, been difficult to accomplish. We will, however, make determined efforts to address this in the next iteration of the program.

Second, the emphatic request by students (in all three summers of the initial program) for increased levels of group work and group activities should not be ignored. This will need to be balanced very carefully with faculty recommendations for more time spent by students working individually on research projects with 'less outside things to do'. The apparent conflict between the traditional, often solitary, nature of science and engineering research, the need for interdisciplinarity and the concerted efforts of multiple researchers in cutting-edge nanotechnology research, and the desire expressed by students for more group work and an emphasis on the social aspects of learning [13–15, 17, 58] will be of particular concern not only for future offerings of the NANOPAC-REU program, but for similar efforts elsewhere.

Third, the 'social and ethical issues' component of the program will need to be restructured. Even though participating faculty and students agreed that such issues were of particular interest to the science/engineering research community (and, in some cases, expressed the necessity for such issues to be considered), there is scant evidence that any such considerations were substantively incorporated into the design and subsequent performance of the respective research projects. An increasing number of researchers in engineering ethics and engineering education have advocated that social and ethical concerns be treated not merely as an 'add-on' to the main business of research, but as an integral part of the research process, from conceptualization to design to execution to applications development [48, 59–64]. This will necessitate closer collaboration between laboratory researchers, science and engineering education researchers, and researchers with expertise in the philosophy and ethical aspects of science and engineering research.

Fourth, closer attention will need to be paid to methods of documentation, assessment and evaluation of what future students learn and are able to do as a result of their participation in the program. During the initial three-year period of the program, several participating faculty voiced their desire for more 'tangible' student outcomes at the conclusion of the program, such as formal presentations (instead of the relatively informal poster sessions) and publishable technical reports. Although formal peer-reviewed conference presentations and publications were encouraged, they were not required of the students, for reasons we have discussed above. However, we agree with Condren *et al.* [65] that 'sharper measures of student learning' may be ascertained via the use of pedagogical tools such as ConcepTests, portfolios, interviews, scoring rubrics and concept maps (p. 554), and we will consider an appropriate selection of such tools for use in future programs. Here again, a careful balance will need to be established so that the time needed to properly administer the assessment instruments does not detract appreciably from the time spent by undergraduates on their laboratory research experiences.

IMPLICATIONS FOR FURTHER WORK AND CONCLUDING COMMENTS

Ultimately, the accomplishments of the NANOPAC-REU program and similar efforts at other institutions to provide research and education experiences for undergraduates in nanoscale science and technology will have a number of implications for undergraduate, postgraduate and doctoral-level engineering education.

Chang [4], Roco [5], Uddin and Chowdhury [66] and Shapter *et al.* [67] all have pointed to the importance of developing nanotechnology education programs at the undergraduate level in order to meet future global needs for continuing research, education and employment in this field. Traditional undergraduate engineering training has been characterized as 'inadequate to meet the challenges presented by this dynamic environment', hence the need to 'reform engineering curricula at the undergraduate degree level and aiming at all degree levels' [4]. At the University of Central Florida, the NANOPAC-REU program has provided the basis on which an undergraduate degree track in nanoscale science and technology has recently been developed. Students enrolled in the degree track take specialization courses in science and engineering subjects, including six modular courses in nanotechnology (i.e. nanomaterials process engineering; nanomaterials characterization and application; nanophysics; nanobiotechnology; nanophotonics; and ethical and societal implications of nanotechnology research). Two primary goals of the degree are to guide students toward pursuing postgraduate studies in the nanotechnology field, and/or to obtain employment opportunities in nanotechnology-related industries [68]. Similar to the challenges articulated by the developers of the first undergraduate nanotechnology degree in Australia offered at Flinders University [67], a major concern for other undergraduate degree offerings in nanotechnology will be that of providing a sufficiently rigorous science content background so that students acquire the necessary fundamental academic competencies in biology, chemistry and physics. Related challenges for developers of undergraduate degree programs in nanoscale science and engineering also will include the need to prepare students, who, in addition to having a firm background in the basic sciences, also are able to articulate the nature of their work to a wider audience [69–71], are sensitive to the social and ethical issues associated with advances in nanotechnology [61, 63, 64], and who have a grasp of the wider political and economic implications of nanotechnology research and education [72].

The increasing popularity of undergraduate research experiences in nanotechnology similar to those provided by UCF's NANOPAC-REU program, and the corresponding development of entire undergraduate degree programs in nanotechnology hold implications for the academic preparation of students intending to pursue advanced-level studies and research in nanotechnology. Traditionally, advanced-level studies and research in science and engineering have necessitated a rather narrow and exclusive focus in a particular specialty or sub-field. Given the highly interdisciplinary nature of nanotechnology research (where the physical sciences, biological sciences and engineering now converge at the nanoscale), there now is a need for students and researchers to be competent in more than one field. Two internationally prominent advanced degree programs in nanotechnology—i.e. the M.Sc./Masters Training Package in Nanoscale Science and Technology jointly offered by the University of Leeds and the University of Sheffield in the UK [73] and the Ph.D. program in Nanotechnology at the University of Washington in the US [74]—both exemplify this approach. The Master's degree at the Universities of Leeds and Sheffield, respectively, has the distinction of being the first such degree in the UK, and 'provides a highly interdisciplinary learning experience to enable single-discipline graduates to contribute effectively to the research, development and commercial exploitation of nanotechnology' (www.ee.leeds.ac.uk/nanomsc/). Admission protocols for the Ph.D. in Nanotechnology at the University of Washington (the first such doctoral degree in the US) require prospective students to first apply for postgraduate study in one of nine disciplinary 'home' departments, after which application is made for admission to the doctoral program in nanotechnology. Students are required to fulfill academic requirements both of the 'home' department and the nanotechnology program, leading to the Ph.D. in Nanotechnology and the chosen discipline (http://www.nano.washington.edu/education/admission.html). We speculate that, as more institutions develop REU-type programs and entire undergraduate degree programs in nanotechnology, admission requirements to advanced degree programs will change accordingly, given that undergraduate academic backgrounds in science and engineering will be considerably more interdisciplinary than is currently the case.

As we have learned, the process of developing high-quality research and education experiences in nanotechnology for academically able university undergraduates in science and engineering has been an important and a complex one. No less complex will be the task faced by the science and engineering community to address the associated issues and implications we have presented here for discussion.

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REFERENCES

1. *National Nanotechnology Initiative* (http://www.nano.gov, 2004).
2. M. C. Roco and W. S. Bainbridge (eds.), *Societal Implications of Nanoscience and Nanotechnology*, National Science Foundation, Arlington, VA (2001), p. 1.
3. M. C. Roco, The US National Nanotechnology Initiative after 3 years (2001–2003), *J. Nanoparticle Res.*, **6** (2004), pp. 1–10.
4. J. P. Chang, Challenges in engineering education of technology (guest editorial), *International Journal of Engineering Education*, **18** (2002), pp. 486–487.
5. M. C. Roco, Nanotechnology: A frontier for engineering education, *International Journal of Engineering Education*, **18** (2002), pp. 488–497.
6. National Science Foundation, *Research Experiences for Undergraduates* (http://www.nsf.gov/home/crssprgm/reu/start.htm, 2004).
7. National Research Council, *Transforming Undergraduate Education in Science, Mathematics, Engineering and Technology*, National Academy Press, Washington, DC (1999).
8. University of Central Florida, *NANOPAC-REU research projects* (http://nanotech.research.ucf.edu/nanopac_projects.html, 2004).
9. National Science Foundation, *Women, Minorities and Persons with Disabilities in Science and Engineering*, NSF/Division of Science Resource Statistics (NSF 03-312), Arlington, VA (2003).
10. National Science Foundation, *Women, Minorities and Persons with Disabilities in Science and Engineering*, NSF/Division of Science Resource Statistics (NSF 04-317), Arlington, VA (2004).
11. G. Sonnert and G. Holton, *Who Succeeds in Science? The Gender Dimension*, Rutgers University Press, New Brunswick, NJ (1995).

12. S. T. Hill, *Blacks in Undergraduate Sience and Engineering Education*, National Science Foundation, Washington, DC (1992).
13. J. S. Brown, A. Collins and P. Duguid, Situated cognition and the culture of learning, *Education Researcher*, **18** (1989), pp. 32–42.
14. J. Lave and E. Wenger, *Situated Learning: Legitimate Peripheral Participation*, Cambridge University Press, Cambridge, UK (1991).
15. G. Saloman and D. N. Perkins, Individual and social aspects of learning, *Rev. Res. Ed.*, **23** (1998), pp. 1–24.
16. J. D. Bransford, A. L. Brown and R. R. Cocking (eds.), *How People Learn: Brain, Mind, Experience and School*, National Academy Press, Washington, DC (1999).
17. A. E. Sweeney and J. A. Paradis, Developing a laboratory model for the professional preparation of future science teachers: A situated cognition perspective, *Res. Sci. Ed.*, **34** (2004), pp. 195–219.
18. A. K. Ditcher, Effective teaching and learning in higher education with particular reference to the undergraduate education of professional engineers, *International Journal of Engineering Education*, **17** (2001), pp. 24–29.
19. C. Chin and D. E. Brown, Learning in science: A comparison of deep and surface approaches, *J. Res. Sci. Tchng*, **37** (2000), pp. 109–138.
20. J. E. Mills and D. F. Treagust, Engineering education: Is problem-based or project-based learning the answer? *Australasian Journal of Engineering Education* (2003) (http://www.aaee.com.au/journal/2003/mills_treagust03.pdf).
21. J. C. Perrenet, P. A. J. Bouhuijs and J. G. M. M. Smits, The suitability of problem-based learning for engineering education: Theory and practice, *Tchng. Higher Ed.*, **5** (2000), pp. 345–358.
22. J. Luft, *Group Processes: An Introduction to Group Dynamics* (3rd edition), Mayfield Publishing Company, Palo Alto, CA (1984).
23. R. H. Bruning, G. J. Schraw and R. R. Ronning, *Cognitive Psychology and Instruction* (3rd edition), Merrill/Prentice-Hall, Upper Saddle River, NJ (1999).
24. H. Etzkowitz and L. Leydesdorff (eds.), *Universities and the Global Knowledge Economy: A Triple Helix of University-Industry-Government Relations*, Pinter, London, UK (1997).
25. University of Central Florida, *Office of Technology Transfer* (http://tt.research.ucf.edu/, 2004).
26. University of Central Florida Technology Incubator (http://www.incubator.ucf.edu/, 2004).
27. L. Mazzola, Commercializing nanotechnology, *Nature Biotechnology*, **21** (2003), pp. 1137–1143.
28. R. Paull, J. Wolfe, P. Hébert and M. Sinkula, Investing in nanotechnology, *Nature Biotechnology*, **21** (2003), pp. 1144–1147.
29. M. W. Martin and R. Schinzinger, *Ethics in Engineering* (3rd edition), McGraw-Hill, NY (1996).
30. R. Spier, *Ethics, Tools and the Engineer*, CRC Press LLC, Boca Raton, FL (2001).
31. L. Mumford, *Technics and Civilization* (first published in 1934), Harcourt, Brace & World, Inc., NY (1963).
32. J. Ellul, *The Technological Society*, Knopf, NY (1967).
33. J. Ellul, *The Technological System*, Continuum, NY (1980).
34. A. Feenberg, *Critical Theory of Technology*, Oxford University Press, Inc., NY (1991).
35. W. H. Vanderburg, *The Labyrinth of Technology*, University of Toronto Press, Toronto, Canada (2000).
36. A. E. Sweeney, S. Seal and P. Vaidyanathan, The promises and perils of nanoscience and nanotechnology: Exploring emerging ethical issues, *Bulletin Sci., Tech. & Society*, **23** (2003), pp. 236–245.
37. R. E. Yager, STS: Thinking over the years, *The Sci. Teacher*, **57** (1990), pp. 52–55.
38. R. E. Yager, *Science/Technology/Society as Reform in Science Education*, State University of New York Press, Albany, NY (1996).
39. R. P. Feynman, There's plenty of room at the bottom: An invitation to enter a new field of physics, lecture presented at the annual meeting of the American Physical Society, California Institute of Technology, December 29th, 1959 (available at: http://www.zyvex.com/nanotech/feynman.html).
40. K. E. Drexler, *Engines of Creation*, Anchor, NY (1987).
41. K. E. Drexler, *Nanosystems: Molecular Machinery, Manufacturing and Computation*, Wiley Interscience, NY (1992).
42. R. Kurzweil, *The Age of Intelligent Machines*, MIT Press, Cambridge, MA (1990).
43. R. Kurzweil, *The Age of Spiritual Machines: When Computers Exceed Human Intelligence*, Viking Press, NY (1999).
44. R. Kurzweil, Promise and peril: Genetics, nanotechnology and robotics in the 21st century, in: M. E. Winston and R. D. Edelbach (eds.), *Society, Ethics and Technology* (2nd edition), Wadsworth Group/Thomson Learning, Belmont, CA (2003), pp. 248–253.
45. W. Joy, *Why the Future Doesn't Need Us* (http://www.wired.com/wired/archive/8.04/joy.html, 2000).
46. R. C. Merkle, Nanotechnology: What will it mean? *IEEE Spectrum* (January 2001), pp. 19–20 (http://www.merkle.com).
47. L. Leydesdorff and H. Etzkowitz, Emergence of a triple helix of university–industry–government relations, *Sci. and Public Policy*, **23** (1996), pp. 279–286.
48. A. Mnyusiwalla, A. S. Daar and P. A. Singer, 'Mind the gap': Science and ethics in nanotechnology, *Nanotech.*, **14** (2003), pp. R9–R13 (http://stacks.iop.org/Nano/14/R9).
49. Accreditation Board for Engineering and Technology, *Engineering Criteria 2000: Criteria for Accrediting Engineering Programs*, ABET, Baltimore, MD (2000).
50. American Society for Engineering Education, *How Do You Measure Success? Designing Effective Processes for Assessing Engineering Education*, ASEE, Washington, DC (1998).
51. P. T. Knight and W. M. Banks, The assessment of complex learning outcomes, *Global Journal of Engineering Education*, **7** (2003), pp. 39–49.
52. S. Isaac and W. B. Michael, *Handbook in Research and Evaluation for Education and the Behavioral Sciences* (3rd edition), Educational and Industrial Testing Services, San Diego, CA (1997).

53. R. L. Linn and N. E. Gronlund, *Measurement and Assessment in Teaching* (8th edition), Prentice-Hall, Upper Saddle River, NJ (2000).
54. N. K. Denzin and Y. S. Lincoln (eds.), *Handbook of Qualitative Research* (2nd edition), Sage Publications, Thousand Oaks, CA (2000).
55. E. J. Davidson, *Evaluation Methodology Basics: The Nuts and Bolts of Sound Evaluation*, Sage Publications, Thousand Oaks, CA (2005).
56. B. M. Olds and R. L. Miller, Assessing a course or project, in *How Do You Measure Success?: Designing Effective Processes for Assessing Engineering Education*, American Society for Engineering Education, Washington, DC (1998), pp. 35–43.
57. *Nanotechnology Law & Business: A Journal for Attorneys, Entrepreneurs and Investors Involved in Small Scale Technologies* (http://pubs.nanolabweb.com/nlb/, 2005).
58. S. H. Russell, *Evaluation of NSF Support for Undergraduate Research Opportunities: 2003 NSF-Program Participant Survey*, SRI International, Arlington, VA (2004).
59. W. H. Vanderburg, Preventive engineering: Strategy for dealing with negative social and environmental implications of technology, *J. Prof. Issues Engng. Ed. & Practice*, **121** (1995), pp. 155–160.
60. W. H. Vanderburg and N. Khan, How well is engineering education incorporating societal issues?, *International Journal of Engineering Education*, **83** (1994), pp. 357–361.
61. R. Devon and I. van de Poel, Design ethics: The social ethics paradigm, *International Journal of Engineering Education*, **20** (2004), pp. 461–469.
62. I. van der Poel, H. Zandvoort and M. Brumsen, Ethics and engineering courses at Delft University of Technology: Contents, educational setup and experiences, *Sci. & Engng. Ethics*, **7** (2001), pp. 267–282.
63. R. Devon, Towards a social ethics of engineering: The norms of engagement, *International Journal of Engineering Education*, **88** (1999), pp. 87–92.
64. G. Hauser-Kastenberg, W. E. Kastenberg and D. Norris, Towards emergent ethical action and the culture of engineering, *Sci. & Engng. Ethics*, **9** (2003), pp. 377–387.
65. S. M. Condren, J. G. Breitzer, A. C. Payne, A. B. Ellis, C. D. Widstrand, T. F. Kuech and G. C. Lisensky, Student-centered, nanotechnology-enriched introductory college chemistry courses for engineering students, *International Journal of Engineering Education*, **18** (2002), pp. 550–556.
66. M. Uddin and A. R. Chowdhury, Integration of nanotechnology into the undergraduate engineering curriculum, paper presented at the International Conference on Engineering Education, August 6–10, 2001, Oslo, Norway (http://www.actionbioscience.org/education/uddin_chowdhury.html).
67. J. G. Shapter, M. J. Ford, L. M. Maddox and E. R. Waclawik, Teaching undergraduates nanotechnology, *International Journal of Engineering Education*, **18** (2002), pp. 512–518.
68. University of Central Florida, Undergraduate degree program in Liberal Studies, Nanoscience and Nanotechnology track (http://www.cas.ucf.edu/liberal_studies/nano.php, 2004).
69. S. C. Florman, *The Existential Pleasures of Engineering*, St. Martin's Press, New York (1976).
70. S. C. Florman, *The Civilized Engineer*, St. Martin's Press, New York (1987).
71. S. C. Florman, *The Introspective Engineer*, St. Martin's Press, New York (1996).
72. National Academy of Engineering, *The Engineer of 2020: Visions of Engineering in the New Century*, National Academies Press, Washington, DC (2004).
73. R. W. Kelsall, The Master's training package in nanoscale science and technology, *International Journal of Engineering Education*, **18** (2002), pp. 506–511.
74. V. Vogel and C. T. Campbell, Education in nanotechnology: Launching the first Ph.D. program, *International Journal of Engineering Education*, **18** (2002), pp. 498–505.

APPENDIX

(Names of REU students are indicated with an asterisk.)

Refereed journal/Proceedings publications

W. Li, S. Seal, E. Megen*, J. Ramsdell, K. Scammon, G. Lelong, L. Lachal and K. A. Richardson, Physical and optical properties of sol-gel nano-silver doped silica film on glass substrate as a function of heat-treatment temperature, *Journal of Applied Physics*, **93** (2003), pp. 9553–9561.

A. Agarwal, K. Rea*, S. Wannaparhun, S. Seal, N. B. Dahotre and T. McKechnie, Aluminum based nanostructured composite coatings: Processing, microstructure and wear behavior, in S. Seal, N. B. Dahotre, J. J. Moore, C. Suryanarayana and A. Agarwal (eds.), *Surface Engineering in Materials Science II*, TMS Proceedings (2003), pp. 81–89.

D. Bera, S.C. Kuiry, M. McCutchen*, A. Kruize, H. Heinrich, M. Meyyappan and S. Seal, In-situ synthesis of palladium nanoparticle filled carbon nanotubes using arc-discharge in solution, *Chem. Phys. Lett.*, **386** (2004), pp. 364–368.

D. Bera, S. C. Kuiry, M. McCutchen*, H. Heinrich, G. C. Slane and S. Seal, In-situ synthesis of carbon nanotubes decorated with palladium nanoparticles using arc-discharge in solution method, *Journal of Applied Physics*, **96** (2004), pp. 5152–5157.

T. Laha, K. Balani, B. Potens, M. Andara*, A. Agarwal, S. Patil and S. Seal, Plasma engineered nanostructured spherical aluminum oxide powders, in S. M. Mukhopadhyay, J. Smugeresky, S. Seal, N. B. Dahotre and A. Agarwal (eds.), *Fifth Global Innovations Symposium on Materials Processing*, TMS Proceedings (2004), pp. 103–112.

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Pallavoor 'Vaidy' Vaidyanathan is the Assistant Vice-President for Research at the University of Central Florida. He coordinates multidisciplinary research and education projects. His interests include materials technologies and education, both formal and informal.

Sudipta Seal is Professor in the Advanced Materials Processing and Analysis Center (AMPAC) and the Department of Mechanical, Materials & Aerospace Engineering (MMAE) at the University of Central Florida. His research interests include surface engineering, and nanoscale science and technology, with emphasis on bulk nanostructures and nano-biotechnology applications. He currently serves as the Nanoinitiative Coordinator at UCF.