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Essay

Bioengineering and Bioinformatics Summer Institutes: Meeting Modern Challenges in Undergraduate Summer Research

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Summer undergraduate research programs in science and engineering facilitate research progress for faculty and provide a close-ended research experience for students, which can prepare them for careers in industry, medicine, and academia. However, ensuring these outcomes is a challenge when the students arrive ill-prepared for substantive research or if projects are ill-defined or impractical for a typical 10-wk summer. We describe how the new Bioengineering and Bioinformatics Summer Institutes (BBSI), developed in response to a call for proposals by the National Institutes of Health (NIH) and the National Science Foundation (NSF), provide an impetus for the enhancement of traditional undergraduate research experiences with intense didactic training in particular skills and technologies. Such didactic components provide highly focused and qualified students for summer research with the goal of ensuring increased student satisfaction with research and mentor satisfaction with student productivity. As an example, we focus on our experiences with the Penn State Biomaterials and Bionanotechnology Summer Institute (PSU-BBSI), which trains undergraduates in core technologies in surface characterization, computational modeling, cell biology, and fabrication to prepare them for student-centered research projects in the role of materials in guiding cell biology.

INTRODUCTION

Although summer research provides the best opportunities for undergraduates to engage in a substantive research project before graduate school, there continue to be some key challenges to achieving a successful summer experience. First, the short (typically 10 wk) summer period makes completing a meaningful project a challenge, particularly if the project involves open-ended research. In fact, most 10-wk programs have a week at the beginning devoted to orientation and a week at the end to symposia, presentations, or project summary reports, leaving 8 wk to learn about the "big picture" of the research, familiarize oneself with experimental methods, design experiments, conduct them, and analyze the data. Because of this arduous schedule, summer research programs, although invaluable tools to expose students to research, may have limited impact in increasing competency and confidence (Kardash, 2000). Thus, there may be an opportunity to design summer research programs that are more effective in recruiting, training, and retaining future scientists. Second, students often do not bring new skills to the research, which can be a challenge for the research mentor who devotes a substantial amount of time training students to do incomplete work for a short period of time (Kardash, 2000). Such a program can become discouraging for even the most altruistic faculty member when substantial time is invested in mentoring students to an unsatisfactory end, only to see that students leave without a successful research experience and perhaps with diminished prospects for graduate school. The use of graduate student mentors to assist in advising, at its best,

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can provide the graduate student with mentoring experience and provide the undergraduate researcher with an age-matched coscientist; but at its worst, the undergraduate students flounder for the summer, become discouraged, and merely add a line to their resumes. The question arises as to whether a program can be designed in such a way to ameliorate these problems and help students and faculty reach the goal of quality summer research.

MEETING THE CHALLENGES: BIOENGINEERING AND BIOINFORMATICS SUMMER INSTITUTES

The new national network of Bioengineering and Bioinformatics Summer Institute (BBSI) programs (see http://bbsi.eeicom.com) established by the National Science Foundation (NSF) and the National Institute of Biomedical Imaging and Bioengineering (NIBIB) intends to accelerate bioengineering and bioinformatics education through intense didactic and hands-on training in advanced technologies and methodologies capable of addressing modern problems in biology, physiology, and health care. In general, the intent of the BBSI program is to foster a research experience that has an enhanced learning component beyond that of traditional REUs (research experience for undergraduates), which emphasize mentor–student pairing (Munshi *et al.*, 2006). Responses to this call for proposals have resulted in 13 BBSIs with diverse approaches to interdisciplinary training in bioengineering or bioinformatics that attract students from the biological sciences, computer sciences, engineering, mathematics, and physical sciences (see http://bbsi.eeicom. com). Most of these programs incorporate didactic training of core competencies and individual research projects consistent with problem-based learning approaches and promote student–student and student–mentor interaction through research teams, social events, and scientific forums (see Table 1).

PEDAGOGY GUIDING PROGRAM DEVELOPMENT

These programs attempt to incorporate the best practices learned from pedagogy and research into existing summer undergraduate programs. For example, Frantz *et al.* (2006) compiled data documenting the efficacy of collaborative learning and focused instruction before embarking on research projects. Their studies suggested that both collaborative- and apprentice-type models of student development enhanced students' attitudes toward science and confidence with science skills and concepts, but only collaborative learning environments significantly enhanced students' ability to perform experiments, a skill of particular interest to faculty mentors (Frantz *et al.*, 2006). This finding is consistent with consensus reached at the Whitaker Bioengineering Summit and summarized by Perreault *et al.* (2006), which identified best practices in engineering that focused on core competencies (or skills). These skills included engineering reasoning and problem solving, experimental design and data analysis, making measurements and interpreting data

Table 1. Didactic components of BBSIs

Lead institution	Institute concentration	Main didactic component (from the Web)	URL
California State University	Bioinformatics	3-wk lecture + workshops	Instructional1.calstatela.edu/jmomand2
Clemson University	Biomaterials	Hands-on mini-workshops	www.ces.clemson.edu/bio/bbsi
Harvard/MIT	Biomedical Optics	Biomedical optics course	web.mit.edu/hstsummer/BiomedicalOptics.html
Iowa State University	Computational and Systems Biology	Short course	www.bioinformatics.iastate.edu/BBSI
New Jersey Institute of Technology	BioMEMS	Short course	www.njit.edu/v2/bme/SI
Oakland University	Bioengineering and Health Informatics	Course on research skills	sibhi.secs.oakland.edu
Oregon State University	EcoInformatics	4-wk course	eco-informatics.engr.oregonstate.edu
Penn State University	Biomaterials and Bionanotechnology	Short courses + workshops	www.bbsi.psu.edu
Texas A&M University	Vascular Bioengineering	2-wk course	ebat.tamu.edu/programs
University of Minnesota	Bioinformatics	Course + workshops	www.bsi.umn.edu
University of Pittsburgh	Computational Biology	Course + workshop	www.ccbb.pitt.edu/bbsi
Virginia Commonwealth University	Bioinformatics	Course	www.vcu.edu/csbc/bbsi
Virginia Tech	Computational Systems Biology, Bio-imaging	Course + workshops	www.bbsi.sbes.vt.edu

Each BBSI is focused on a distinct area of Bioengineering and Bioinformatics. Didactic components also differ but are a main focus of the undergraduate research experience. Details of programs and their didactic content can be found using the URL provided.

from biological systems, laboratory technique, communications, and maturity and responsibility.

Similarly, the consensus of participants from the 2004 National Academies Summer Institute on Undergraduate Education in Biology was that the best way to increase science competency is through active learning that includes enhanced student–faculty interaction, integrated tools for monitoring and encouraging student progress, and development of methods to accommodate diversity of backgrounds, learning styles, goals, genders, and ethnicities (Wood and Handelsman, 2004). In response to these needs, there has been excellent progress in tools to develop curriculum and programs that encourage excellence and competence in young scientists, including a focus on problem-based learning (Newstetter, 2006) and design of integrated training and assessment tools (Lemons and Griswold, 1998). As the skill set needed for success in science increases in sophistication and depth, there is a need to implement these pedagogical observations through carefully planned summer research programs for undergraduates. In general, when undergraduates engage in research, they are more likely to pursue advanced degrees and they feel more competent to engage in research.

These results and other outcomes of undergraduate research programs were compiled in a major survey conducted by SRI International and reported in *Science* by Russell *et al.* (2007). In this survey, conducted between 2003 and 2005, respondents indicated positive benefits of research experiences at the undergraduate level. Interestingly, that survey found that commonly used mechanisms of reinforcing skills learned, such as final reports, had little bearing on perceived positive outcomes by participants. Instead, attending conferences, mentoring other students, and authoring journal papers were activities cited as leading to positive outcomes and increased interest in a career in science. In addition, increasing the duration of research experiences and the variety of research activities also correlated with positive outcomes. Seymour *et al.* (2004) recently compiled a comprehensive survey of literature on undergraduate research program design. They found that undergraduate research programs could be grouped into retention programs, career promotion programs, and research apprenticeships. Retention programs are those that steer undergraduates toward science and engineering careers through positive research experience, which simulate the graduate research environment. Career promotion programs are ones in which the principal goal is recruitment, either into the field in general or to the institution in particular. Research apprenticeships are a model in which students incorporate mastery of concepts through research-based learning through discovery.

We suggest that the BBSI provides a distinct model, which we call instruction-enhanced research. Of course, this model shares successful aspects of the research apprenticeships, research-based learning, and monitoring of student progress, but fosters increased understanding and competence in research through an intense traditional didactic setting, such that research proceeds from a foundation of theoretical knowledge. In this way, the model is similar to one described by Frantz *et al.* (2006), in which 2 wk of didactic training precedes the research experience. Most BBSIs favor an even more extensive didactic component and are focused on areas of bioengineering and bioinformatics, in particular (Table 1). This model is similar to the lecture-lab environment of traditional science and engineering curricula with the significant difference in that research is open-ended and innovative. One example of this model is at the University of Pittsburgh, which trains students in the fundamental underpinnings, skills, and software, in molecular modeling followed by a research apprenticeship with a bioinformatics mentor (Munshi *et al.*, 2006). The Penn State (PSU) program trains students in microscopy, surface characterization, and modeling, in order to equip them to enhance existing faculty mentor research at the interface of materials and cell biology. Other BBSI didactic approaches are listed in Table 1. Program details can be found using the URLs provided in the table.

The end goal of the BBSI program is to provide formal instruction to increase student competence and faculty satisfaction without sacrificing "essential components of undergraduate research" as outlined in Lopatto (2003). In that study, many of the faculty responses focused on the faculty perception of benefit for the students. Because the intent of programs is to enrich student experience and enhance skills in order to increase their awareness and qualifications for graduate-level

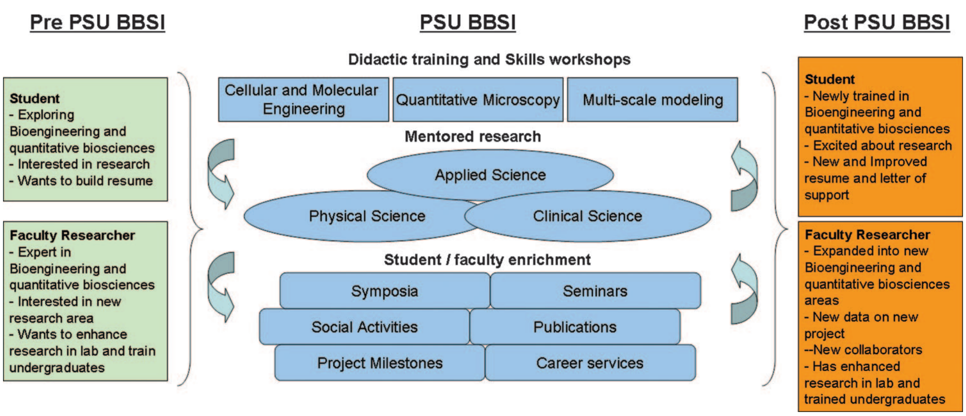

Figure 1. Concept map of BBSI training activities. Students exploring graduate work in bioengineering (either bioengineers or students from non-bio-related engineering majors, science, and math) are paired with faculty mentors in bioengineering, chemistry, engineering science, and medicine. Faculty are encouraged to explore ways in which workshop activities can be incorporated into student projects. Post-BBSI, students have enhanced their graduate applications and learned new bioengineering methodologies.

research, the focus on student benefits is reasonable. However, in the face of other competing pressures (e.g., teaching, research, and service) some faculty find such altruism unsustainable and will not mentor undergraduates for the simple reason that "the effort you put in is greater than the benefit you get out." Thus, it is important to design programs that ensure faculty satisfaction with student performance.

PSU-BBSI: BIOENGINEERING OF CELLS AND MOLECULES AT SURFACES

Consistent with other BBSIs that designate a clear intellectual focus or theme, the PSU-BBSI aims to focus undergraduate research on the cellular and molecular underpinnings of the response of physiological systems to foreign materials (Figure 1). Traditionally, understanding of the fundamental aspects of cell behavior on this scale has not been accessible to the average researcher. However, new and readily accessible tools in cell biology are permitting novel interrogation of cellular processes; methods in quantitative and ultramicroscopy are permitting single-molecule investigations into cellular behavior on unprecedented length and time scales (Trache and Meininger, 2005; Becker *et al.*, 2006; Gullapalli *et al.*, 2007); computational methods in bioengineering are now well suited for developing models to summarize experimental data and predict biological phenomena on multiple scales (Alves *et al.*, 2006; Ferko *et al.*, 2006).

In addition, new materials, with controllable properties at the nanoscale, are being used to manipulate and control

Table 2. Overview of research activities at the PSU-BBSI

Member Lab PI	Project title	Workshops skills integrated into research (reported by students)
Peter Butler Bioengineering	Spectroscopic imaging of cell adhesion	Quantitative microscopy, atomic force microscopy, cell culture, bioethics
Henry Donahue Orthopedics	Development of an optimized bioreactor for musculoskeletal tissue engineering.	Cell culture, quantitative microscopy, solidworks
Melik Demirel Engineering Science	Molecular dynamics simulation of GFP	Computational modeling programs
Cheng Dong Bioengineering	Project in biomechanics of cancer cells	Cell culture, bioethics, and confocal microscopy
Ryan Clement Bioengineering	Fabrication of electrode-nerve interfaces	Solidworks, confocal imaging, and COMSOL
Andrew Ewing Chemistry	Project in nano-scale manipulation of cell membranes	Quantitative microscopy, atomic force microscopy, cell culture
William Hancock Bioengineering	Optimizing methods for directing movement of microtubules across microfabricated surface	Molecular dynamics, fluorescence/confocal microscopy, and cell culture
Ahmed Heikal Bioengineering	Biophotonics and cancer screening	Quantitative microscopy, atomic force microscopy, cell culture, bioethics
A. Daniel Jones Chemistry	Project in mass spectrometry	Mass spectrometry of surfaces
Christine Keating Chemistry	Synthesizing model "cells" comprised of lipid vesicles encapsulating polymers	Quantitative microscopy, atomic force microscopy, molecular biology
Herbert Lipowsky Bioengineering	Synthesizing an artificial glycocalyx on glass	Microscopy, surface modification
Tao Lowe Bioengineering, Surgery	Drug delivery	SEM/TEM, AFM, and confocal microscopy workshops
Keefe Manning Bioengineering	Thrombosis in artificial heart and valves	Solid works, electron microscopy, bioethics, and computational methods in bioengineering.
Erin Sheets Chemistry	Patterning biomimetic membranes to investigate their biophysical properties	Quantitative microscopy, atomic force microscopy, cell culture, bioethics
Christopher Siedlecki Bioengineering, Surgery	Atomic force microscopy of plasma proteins	Atomic force microscopy, electron scanning microscopy, and 3D modeling workshop
Alan Snyder Bioengineering, Surgery	Platelet adherence to nanotextured surfaces	Confocal microscopy, electron microscopy, computational methods for bioengineering
Erwin Vogler Materials Science	Cell-protein-surface interactions in tumor cell migration	Biomaterials surface characterization
Paul Weiss Chemistry	Controlling cell adhesion to surfaces through membrane modulation	Confocal microscopy and STM
Jeffrey Zahn Bioengineering	Low Reynolds number flow and pressure in novel micro-electromechanical systems	Micro- and nano-fabrication techniques, validation

Projects are chosen to be broadly related to biomaterials and bionanotechnology. Mentors are encouraged to explore new ways in which techniques learned in workshops can be incorporated into student projects. List includes current and former mentors.

Table 3. Overview of workshops

Workshop	Learning objective
Methods in Cell Culture	Students will be proficient in basic sterile cell culture techniques (thawing, passing).
Genetic Engineering	Students will learn to splice genes, create GFP, and transfect cells.
Quantitative Microscopy	Students will be able to take digital images of live cells using phase/DIC/fluorescence and confocal microscopy.
Atomic Force Microscopy	Students will learn how to use AFM on dry and wet surfaces: follow-up individual training required.
Electron Microscopy	Students will learn how to use EM on dry fixed surfaces: follow-up individual training required.
Solid Modeling	Students will learn basic machining techniques and solid modeling using SolidWorks software.
Computational Methods in Bioengineering	Students will learn basic finite element modeling and applications of COMSOL multiphysics software to biological problems.
Introduction to Molecular Dynamics and Protein Modeling	Students will learn how to obtain protein structures from the protein data bank and run equilibration studies using AMBER.
Bioethics	Students will learn efficient tools for bioethics and discuss modern bioethics challenges.

Workshops follow formal lectures and provide hands-on experience for BBSI students in modern bioengineering techniques and technologies. Students follow up with workshop organizers to develop methods to apply techniques in their research. Every student attends three workshops per year. At least six workshops are given per summer.

biological host responses at the cellular and molecular levels (Helmke and Minerick, 2006). This paradigm of cellular engineering, imaging, and modeling is unique to bioengineering and is opening up exciting possibilities for novel therapeutic interventions, diagnostic tools, and biomaterials. Thus, the PSU-BBSI has designated as its intellectual focus, "bioengineering of cells and molecules at surfaces" with an emphasis on training students in methods that address modern challenges at the material-biology interface. Faculty mentors at Penn State who work at this biology-materials interface and who are experts in cell and molecular biology, quantitative microscopy, and computational modeling, train students to tackle these challenges in the context of cutting-edge research (Table 2). Infrastructure enabling this focus includes an extensive array of core facilities from which to draw for workshop development (Table 3). These facilities

Table 4. Example of project planning

Project milestone	Student submission example
Background: Students were asked to summarize the background of their projects.	"Resent research has shown that cells grown on materials with different elasticities will respond to their environment differently. . . . Because most research tools currently depend heavily on the use of microscopes, it is also important for the new material to have the material properties of glass, i.e. its index of refraction, and can be used in microscopy."
Goal of project: Students confer with their mentors on the goals of the projects (attainable in 10 wk).	"The goal of this project is to coat the glass slides with a new polymer that is more elastic than glass and more similar to in vivo environment, but one that has properties of glass. . . . . Material will be characterized by Atomic Force Microscopy and cell adhesion will be monitored using total internal reflection fluorescence microscopy (TIRF). . . . ."
Materials and Methods: Students were asked to identify the main methods and materials they would use. Students were also given a budget of $1000 for project related supplies.	"We start by spin coating [polymer] and curing it for various times. . . . . Atomic Force Microscopy will be used to detect the roughness of the surface. . . . . Image of the focal adhesions of cells can be obtained using TIRF."
Expected Results: Students were asked to think carefully about what the expected results were.	"[the polymer]. . . . should have a cured index of refraction of 1.56, which is not substantially differently than the glass index of refraction of 1.52. By using TIRF on Thursday, we saw that the polymer works just as well in microscopy as if it was a plain glass slide. . . . ."
References: Students collected at least five references related to their projects.	"Costantino, Santiago. "Two-Photon Fluorescent Microlithography." *Microscopy Research and Technique* 68 (2005) 272–276. May, 31 2007. Discher, Dennis E. and Janmey, Paul, and Wang, Yu-li. "Tissue Cells Feel and Respond to the Stiffness of Their Substrate." *Materials and Biology Science* 310 May 3, 2007 1139–1143. May, 31 2007. . . ."

Students consulted with mentors in week 1 to discuss details of project plan. Project plan was outlined using Gantt charts (see Figure 2).

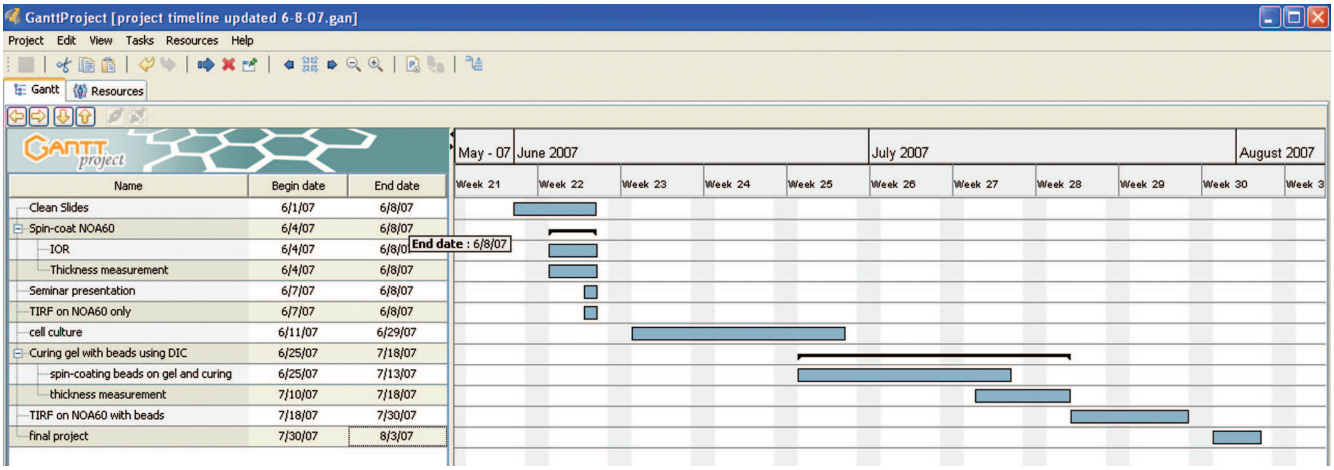

Figure 2. Development of Gantt chart for project implementation. Gantt charts are tools used in management and engineering to plot out project tasks and timelines. Free Gantt chart software (from http://ganttproject.biz/) was used to generate figure, which is a representative example of a Gantt chart submitted in conjunction with representative project plan outlined in Table 5.

include microscopy (atomic force microscopy [AFM], electron microscopy [EM], confocal, optical, and deconvolution microscopy), materials development and characterization, nanoscale manufacturing, and cyber-infrastructure. Our goal for the PSU-BBSI is to provide accelerated training in these areas and to mentor individual and team research projects to prepare undergraduate students to meet these challenges. To assist in implementing problem-based and instruction-enhanced research modalities, we have incorporated some simple tools, borrowed from management methods in industry, to help ensure that students have communicated with their mentors on project definition, have developed detailed components of project completion (deliverables), have enough time to complete a project, to learn new skills that will aid them in future research, and to provide mentor labs with a highly-trained workforce.

Students begin by identifying the key research goals, hypotheses, or design goals and establish specific aims. Stu-

Table 5. PSU-BBSI student demographics

	2003		2004		2005		2006		2007	
	App	Adm	App	Adm	App	Adm	App	Adm	App	Adm
Total no.	101	17	138	20	83	17	88	15	73	16
Female	46	8	67	12	36	10	44	7	37	6
Male	58	9	71	8	47	7	44	8	36	10
Hispanic	N/A	0	9	0	2	1	6	1	3	1
African-American	N/A	0	11	1	7	4	4	2	2	0
Other non-Caucasian	N/A	3	50	5	27	2	20	3	18	2
Caucasian	N/A	14	73	14	42	10	49	9	45	9
Other/not reported			8		5		9		5	4
Average GPA	3.41	3.64	3.42	3.39	3.48	3.45	3.44	3.51	3.59	3.71
Undergraduate	99	13	119	15	74	16	86	14[a]	72	16[a]
First-year graduate	5	2	19	4	9	1	2	0	0	0
Bioengineering	45	13	82	15	53	8	46	5	33	7
Engineering, non-Bio	26	1	24	2	10	4	22	3	11	4
Science, Bio	24	1	21	2	15	5	14	5	20	3
Science, non-Bio	4	2	7	1	4	0	4	2	3	1
Math/Comp. Sci.	2	0	4	0	1	0	2	0	2	1

Statistics of applicants (App) and admitted (Adm) students. Undergraduates were those who completed their sophomore year. Bioengineering includes bioengineering and Biomedical engineering majors; Engineering non-Bio includes chemical, mechanical, and other non-Bio–related engineering majors; science, Bio includes biology, biochemistry, biophysics, and biotechnology; and science, non-Bio includes physics and chemistry. N/A indicates not asked.

[a] One student had obtained an undergraduate degree but was not enrolled in graduate school. Not shown: 26 out of a total of 45 students (58%) returned for a second summer. Generally, if students did not return for a second year, it was because they were admitted to graduate or medical school. Two students were not invited to return.

Table 6. Evaluation of workshops and research experience by students and faculty (from online surveys)

Expression of Student Satisfaction

“I really liked the independence that the program gives us, allowing us to create our own schedules to complete projects.“

“Entering the program, I knew very little about cells or polymer science. Entering this fall semester in Bioengineering, I feel much more comfortable with both my laboratory techniques and my ability to think critically in an intense situation.“

“My research was a very well thought-out project with lots of hands on and troubleshooting time. It was a great introduction to bioengineering without being overwhelmingly biology and chemistry oriented.“

“[The workshops] were informative and it was nice to have them all at the beginning of the summer before we were really busy with experiments etc.“

“BBSI program enabled me to compare working as a researcher vs. going to med school to be a doctor although I'm still undecided about which one to choose.“

“This research experience helped me understand what it is like to work with an advisor to reach a experimental goal. I learned that research isn't just about doing lab work but also reading literatures and fixing obstacles on the way. This experience also opened my eyes to other bioengineering aspects and fields that is being worked on today.“

Expression of Student Dissatisfaction

“While the increased independence was good, my experience was almost a little too independent. I would have liked more interaction with my advisor/professor, whom I only saw occasionally. This would have given my project a bit more focus. Nevertheless, I learned a great deal at BBSI and would definitely do it again if given the chance.“

“I will probably not do research in basic research, but I do want to work in applied research positions. This summer helped me to figure out that basic research was not a bad place to work, but it just is not what I want. I will continue in Bioengineering/Biomedical Engineering.“

“The professors' presentations weren't always understandable, but most students' presentations were good.“

“I understood parts of about 80% of the seminars. Some of them were heavily concentrated in Biology that I haven't yet explored.“

Statements of Faculty Satisfaction

“I liked that the workshops were at the beginning of the summer. It helped the students use their time more productively, since their projects may be ill-defined early on. It also helped them think about ways to integrate the workshop material into the research.“

“The BBSI Students are by far the best undergraduate student I have had in my lab“

“I like how the BBSI students seem to be a well-integrated group. They eat together, play together, and talk about research together as if they enjoy it.“

Statements of Faculty Dissatisfaction

“The BBSI seminars and workshops take the students out of the lab quite a bit, although I must admit that when in the lab, they do not waste time and they work hard and are very motivated.“

“It is a lot of work to take on a BBSI student because of the mentoring responsibilities.“

dents then document their work plan early in the summer using project-planning worksheets (Table 4) and Gantt charts (Figure 2), and in-house training on advanced technology occurs early to provide the student with a sense of competence and the researchers with a trained workforce. Gantt charts are a tool borrowed from management techniques in which tasks are organized, assigned, and designated to be completed at certain times. Progress of task completion is communicated continuously using Gantt chart software from http://ganttproject.biz/. Use of Gantt charts is a simple method to monitor student progress through the summer (Russell *et al.,* 2007). In addition, seminars, advising sessions, and symposia help meet the interests of the students by mentoring them through uncharted waters of research, teaching them how to communicate their research findings, and encouraging them to think beyond their instruments and experiments to begin to shape their futures as researchers at the interface of cell biology and engineering. These program design strategies have helped us implement the best aspects of problem-based learning and have enabled us to balance student needs to complete a meaningful research project and faculty needs of assistance in mentoring and technology training.

ASSESSMENT AND PROGRAM ENHANCEMENTS IN RESPONSE TO SURVEYS AND INTERVIEWS

The program was assessed internally yearly for student satisfaction with housing arrangements and food, workshops, research experience, and mentor–student interaction. Demographics of applicants and participants are shown in Table 5. Survey results for two representative years in which no students overlapped are shown in Figure 3. In contrast to 2007, during which workshops were held early and were actively integrated into research projects, in 2004 the workshops were spaced out over the summer and selected according to student interest, not research needs. Student satisfaction increased (became closer to 1) from 2004 to 2007, especially in the areas related to workshops and research experience. Anecdotal testimony from students and faculty (Table 6) also indicated that integration of workshops and research fostered more creativity in research and led to increased faculty satisfaction and the students' sense of project completion and success. In addition to local dissemination of research findings, BBSI students are encouraged to present their work in national meetings and in peer-reviewed publications as recommended by Russell *et al.* (2007). PSU-BBSI–sponsored research has resulted in more than 17 conference and peer-reviewed publications in the first 5 yr. Examples of peer-reviewed publications coauthored by a PSU-BBSI student are as follows: Paxon *et al.* (2004), Gaumond *et al.* (2004), Leyton-Mange *et al.* (2006), Liu *et al.* (2006), Lim *et al.* (2007), and Ferko *et al.* (2007). We point out that ours is a 2-yr program and that the evidence of benefits of a 2-yr program is found, in part, by the fact that five of six of these peer-reviewed publications feature second-year BBSI students. The BBSI program as a whole is undergoing a major evaluation by an independent research firm contracted by the NSF. Whether approaches outlined here and in other BBSIs have increased positive outcomes over traditional REUs remains to be seen. However, initial compilation of demographics (Table 5) and anecdotal evidence from students suggest that the BBSI will increase the

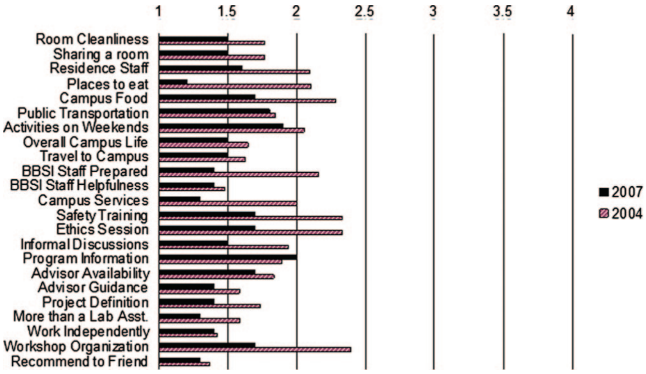

Figure 3. Student satisfaction survey. Students were asked to use Likert scale to state whether they agree with various statements regarding satisfaction with aspects of the program. 1, strongly agree; 2, agree; 3, disagree; and 4, strongly disagree. An average $<$ 2 indicates general agreement or satisfaction and $>$2 indicates general disagreement or dissatisfaction. Results compared are from 2004 and 2007. In 2004 workshops existed but were not integrated into the research experience and were not given early in the summer, as they were in 2007. Representative data derive from separate pools of students.

number of nonbioengineers who consider applying skills from their quantitative disciplines to problems in biology and health care and that bioengineers will broaden the scope of problems they consider through exposure to methodologies not traditionally associated with bioengineering. In addition, comprehensive evaluation of the benefits of a 1- versus a 2-yr program are currently being evaluated.

SUMMARY: BBSI AS A MODEL FOR GUIDED PROBLEM-BASED LEARNING

In an effort to both broaden and deepen the scientific skills of a new workforce, the NSF and the NIBIB have called for the development of the BBSIs to train students in core technologies and methodologies in modern quantitative biology. The PSU-BBSI focuses its training in Biomaterials and Bionanotechnology, two core strengths at Penn State, using a combination of hands-on workshops, student-led seminars, and focused, guided research projects. This interdisciplinary program trains students in cutting-edge technology at the interface of traditional disciplines and increases intellectual diversity in bioengineering. Collectively the BBSIs have developed a wide variety of successful methodologies to train young scientists in highly advanced technologies that are playing an increasingly important role in advancing biology, physiology, and health care. Important goals for this article are to highlight the existence of the BBSIs and to disseminate new strategies for interdisciplinary undergraduate training, with pedagogical underpinnings that will lead to enhanced participation of students in bioengineering and quantitative cell biology research.

Much anecdotal evidence documenting student and faculty satisfaction substantiates the contention that programmatic design can help facilitate meaningful research experiences for students and faculty, while continual monitoring of areas of dissatisfaction ensures continual program improvement. In particular, increased training in technology, even if it borrows time from research, can be an excellent method to increase research productively and satisfaction of both faculty and students. As health care challenges continue to mount, there is an increasing need for a diverse pool of graduate students trained in bioengineering and cell biology methodologies. In response to this challenge, the BBSI program provides multifaceted approaches to undergraduate education resulting in highly trained students prepared for careers in quantitative methods in biology. In addition, the BBSI provides researchers with new avenues of investigation and new technologies in quantitative and analytical methods in biology and opens up for students new opportunities in the development of novel diagnostic and interventional tools in science, engineering, and medicine.

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