Article

Promoting Convergence: The Integrated Graduate Program in Physical and Engineering Biology at Yale University, a New Model for Graduate Education

Dorottya B. Noble†,‡
Simon G. J. Mochrie†,§,¶
Corey S. O'Hern†,§,¶,||,††
Thomas D. Pollard†,‡,‡‡,§§
Lynne Regan†,‡,††,¶¶*

From the †Integrated Graduate Program in Physical and Engineering Biology, ‡Department of Molecular Biophysics and Biochemistry, §Department of Physics, ¶Department of Applied Physics, ||Department of Mechanical Engineering and Materials Science, ††Graduate Program in Computational Biology and Bioinformatics, ‡‡Department of Molecular, Cellular, and Developmental Biology, §§Department of Cell Biology, ¶¶Department of Chemistry, Yale University, New Haven, Connecticut 06520, USA

Abstract

In 2008, we established the Integrated Graduate Program in Physical and Engineering Biology (IGPPEB) at Yale University. Our goal was to create a comprehensive graduate program to train a new generation of scientists who possess a sophisticated understanding of biology and who are capable of applying physical and quantitative methodologies to solve biological problems. Here we describe the framework of the training program, report on its effectiveness, and also share the insights we gained during its development and implementation. The program features co-teaching by faculty with complementary specializations, student peer learning, and novel hands-on courses that facilitate the seamless blending of interdisciplinary research and teaching. It also incorporates enrichment activities to improve communication skills, engage students in science outreach, and foster a cohesive program cohort, all of which promote the development of transferable skills applicable in a variety of careers. The curriculum of the graduate program is integrated with the curricular requirements of several Ph.D.-granting home programs in the physical, engineering, and biological sciences. Moreover, the wide-ranging recruiting activities of the IGPPEB serve to enhance the quality and diversity of students entering graduate school at Yale. We also discuss some of the challenges we encountered in establishing and optimizing the program, and describe the institution-level changes that were catalyzed by the introduction of the new graduate program. The goal of this article is to serve as both an inspiration and as a practical "how to" manual for those who seek to establish similar programs at their own institutions. © 2016 The Authors Biochemistry and Molecular Biology Education published by Wiley Periodicals, Inc. on behalf of International Union of Biochemistry and Molecular Biology, 44(6):537–549, 2016.

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**Address for correspondence to: Lynne Regan, MB&B, PO Box 208114 New Haven CT 06520. E-mail: lynne.regan@yale.edu.*
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Introduction

Cutting edge research in the life sciences is increasingly convergent, with research groups that include scientists with biological, physical, engineering, and computational backgrounds. This development raises questions about how best to train a new generation of students to thrive and become leaders in this new scientific landscape [1–3].

We describe the Integrated Graduate Program in Physical and Engineering Biology (IGPPEB) at Yale University. As the first IGPPEB students are graduating, it is timely to report and reflect on which features are successful, and which have required modification and optimization since their initial implementation. Coincidentally, a short opinion piece on the NIGMS Feedback Loop Blog recently discussed the need to modernize biomedical graduate education and outlined critical issues that should be addressed [4]. These include but are not limited to continually optimizing training strategies, creating and sustaining a diverse workforce, emphasizing mentoring throughout training, incorporating active learning and other evidence-based approaches, training scientists to apply quantitative approaches to biological problems, and preparing students for a variety of careers. The IGPPEB incorporates many of these elements, and therefore, we intend for this report to serve as a roadmap and inspiration for others who seek to implement interdisciplinary graduate research programs.

First, we describe the motivation for starting the IGPPEB and delineate its goals and its administrative structure. We then explain the IGPPEB curriculum, including a detailed description of the courses and enrichment activities, which are a central component of the program. We end by presenting the results of the student assessment of the IGPPEB, and our responses to their concerns. Finally, we discuss the challenges encountered in establishing the IGPPEB, specifying those that we surmounted and those that still remain, and what institutional changes have resulted as a consequence of setting up the program.

Program Overview and Goals

The genesis of the Integrated Graduate Program in Physical and Engineering Biology (IGPPEB) was our realization that many students from physics, engineering, and biology were starting to work in research groups on collaborative and convergent projects. We established *ad hoc* strategies by which to educate the students in areas that were new to them, but we quickly realized that the demand was so great and ever increasing, that it was vital to establish a formal graduate training program. Thus, in the summer of 2008, with seed funding from Yale University, the IGPPEB was formed and the first class matriculated in the fall of 2009. Financial support from the institution was critical to establish the program, in no small part because it allowed us to offer funding for additional students within the home programs.

The goal of the IGPPEB is for students to acquire deep knowledge in a specific area of study and a functional literacy in a wider range of topics (see Table I). Both depth and breadth of expertise is vital to effective interdisciplinary research innovation [2, 5, 6]. The IGPPEB training prepares students not only to approach scientific problems as experts but also be able to view problems from multiple perspectives and to contribute meaningfully to projects as members of an interdisciplinary team.

To achieve these goals, the IGPPEB includes the following elements. The IGPPEB does not grant the PhD degree, so students receive their PhD from their home program and a Certificate of Completion from the IGPPEB program to recognize their successful completion of the program. Therefore, students enter the IGPPEB through one of several home programs in the physical, engineering, and biological sciences. Importantly, participation in the IGPPEB does not increase time to degree. Thoughtful integration of home program and IGPPEB requirements means that the number of additional requirements, beyond those of the home program that students must complete as part of the IGPPEB is at most one course.

The IGPPEB has the following distinguishing features: (1) Coteaching by faculty with different specializations, bringing multiple points of view to the same problem; (2) Peer learning, which engages students in communicating across disciplines and learning from one another; (3) Teamwork, which requires students to develop strategies to work productively with others; (4) Communication skills, vital to many careers, including that of a research scientist; (5) Scientific engagement with the wider community, which exposes students to all areas of science and helps build their scientific network; (6) A strong *esprit de corps* amongst participating students and faculty who form a transdisciplinary network; and (7) Preparation for a variety of careers through the experiences and transferable skills obtained in features 2–5; (8) Definition and tracking of metrics of success and outcomes; (9) Increasing diversity in the STEM workforce; and (10) Incorporation of outreach activities into the program.

IGPPEB Administrative Structure

The IGPPEB Leadership Team is composed of the IGPPEB Director plus three faculty members representing physics, engineering, and biology. The Executive Committee includes the Leadership Team plus at least one faculty member from each home department. The Associate Director (a PhD level position) works closely with the Director, the Leadership Team and the Executive Committee, and acts a liaison between IGPPEB and the home programs to ensure that all policies are in place and all program-related initiatives are working as planned. This structure ensures that any changes in the academic requirements or course scheduling of the home programs are quickly and appropriately incorporated within the IGPPEB and *vice versa*.

IGPPEB Curriculum

The IGPPEB curriculum consists of four core courses plus two primer courses See Fig. 1. The latter are not required but are recommended for students with minimal background in areas outside their undergraduate major.

TABLE I *IGPPEB program goals and the student outcomes and program elements designed to meet these goals*

Program goals	*Elements of the program put in place to meet these goals*
Train researchers to conduct cutting edge research at the interface of physics, engineering, and biology: • Gain a sophisticated understanding of biological problems • Increase appreciation of methods and techniques for wet lab experiments (for physicists and engineers) and for modeling and computation (for biologists)	• IGPPEB core courses • Integrate teaching and research through the Integrated Workshop core IGPPEB course • Co-teaching by IGPPEB faculty with complementary expertise
Attain deep knowledge in one discipline and breadth of knowledge across multiple disciplines	• Home program courses • IGPPEB core courses
Expose students to a broad range of research and faculty labs across disciplines	• Integrated Workshop core IGPPEB course • *Monthly Research in Progress Talks* • *Distinguished Speaker Series* • *Symposia and Retreats*
Develop strong communication skills across disciplines and with non-scientists	• Integrated Workshop core IGPPEB course • Methods and Logic in Interdisciplinary Research core IGPPEB course • *NSF PoLS SRN* • *Second-year presentations in monthly Research in Progress Talks* • *Outreach experiences* • *Short course on science communication* • *Symposia and retreats*
Enhance ability to work in an interdisciplinary team	• Integrated Workshop core IGPPEB course • Methods and Logic in Interdisciplinary Research core IGPPEB course
Build a community that lasts beyond year 1	• IGPPEB Enrichment Activities
Enhance diversity (social backgrounds, ethnicity, and gender) that better reflects the composition of the United States	• Women and minorities in leadership positions • REU program to attract students to apply to IGPPEB • REU students in IGPPEB labs
Foster mentoring across disciplines and experience levels	• Student teaching in IGPPEB courses • Peer learning in IGPPEB courses • *Outreach experiences*

NSF PoLS SRN = National Science Foundation Physics of Living Systems Student Research Network; REU = Research Experiences for Undergraduates; In Italics = *IGPPEB enrichment activities (see "IGPPEB Enrichment Activities Beyond the Core Courses")*

Primer Courses

Boot Camp Biology is a primer course for students with little or no background in biology or chemistry. It introduces students to the basic concepts, techniques and vocabulary of biology, emphasizing what is and is not known. Topics include the molecules of life, the central dogma of molecular biology, cells, and multicellularity. The format encourages student participation in a variety of ways, including classroom discussions of homework problems. Students are also shown a range of equipment and experimental techniques from molecular and cellular biology, because the students may have read about certain techniques but never have seen them in practice.

Mathematical Methods in Biophysics is designed for students with little or no background in physics, engineering, or computer programming. Topics covered include

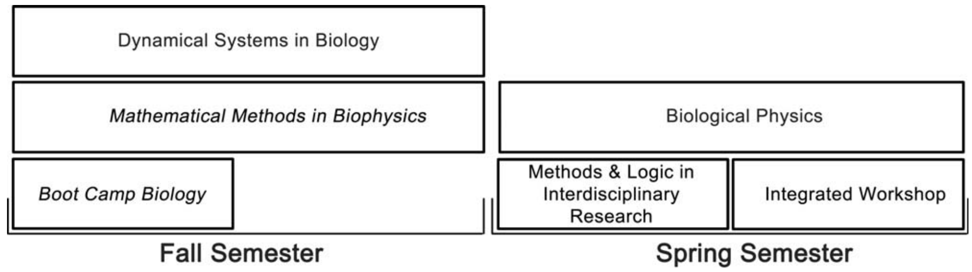

FIG 1 *IGPPEB curriculum including four core courses (regular font) and two optional primer courses (Italics font). Fall and Spring Semesters refer to the semester the courses are offered. The lengths of the boxes indicate whether the courses are half or full semester. Home program courses are not included in this figure.*

linear algebra, differential equations, Bayesian probability, statistics, data and error analysis, Fourier transforms, and programming in MATLAB. Collaborative, interactive work on problem sets during class time is a distinctive feature of the course.

Core Courses

Extensive discussions amongst all founding faculty led to four core courses, which all IGPPEB students take regardless of their undergraduate backgrounds: (1) Methods and Logic in Interdisciplinary Research, (2) Integrated Workshop, (3) Biological Physics, and (4) Dynamical Systems in Biology. These courses had several explicit goals: be relevant for students' future research; include many instances in which students with different backgrounds work together and learn from each other; show different ways to apply quantitative approaches to important problems in biology; include students with different backgrounds working together on hands-on projects; and should be of minimal number, and intensely focused.

Methods and Logic in Interdisciplinary Research

This course aims to develop students' critical thinking by reading and analyzing research papers. The course encourages students to work together and learn from each other, to articulate their opinions, to think creatively and to write succinctly and well. All these skills are vital for success in research and a multitude of other careers.

Each week, students discuss two papers that address related biological problems, but from different perspectives. (see Table II for a sample of the papers used in the course). Students initially meet on their own to discuss the papers. They combine their diverse expertise to ensure that everyone appreciates the overarching goals of the paper and understands the technical aspects of the experiments. This key feature of the course encourages students to work together and to ask each other questions that they might be embarrassed or intimidated to ask when faculty are present.

The same week, after the student-only session, the class meets with two faculty members, who lead wide-ranging discussions. The pairs of faculty have complementary expertise. For example, an experimentalist is paired with a theoretician or a biologist is paired with a physicist or engineer. Each week a different pair of faculty leads the discussion.

The format with two faculty with different expertise leading these sessions (even asking each other questions), strengthens the idea that new insights emerge from viewing scientific questions from a variety of perspectives. The faculty strives to create a supportive environment to bring all of the students into the discussion, but also challenging them, for example, by calling on them to defend their positions. We encourage new faculty to sit in on a class to see how experienced faculty members facilitate discussions and create a fun yet rigorous atmosphere.

At the end of the course, students devise a follow-up experiment, inspired by one of the papers covered in class. They give a short presentation and write a polished abstract on the topic of their proposal.

Integrated Workshop

The goal of this course is for pairs of students from different backgrounds (e.g., biology and physics/engineering or theory and experiment) to work together on hands-on research modules. IGPPEB faculty devise modules requiring a wide variety of skills, so it is unlikely that any student has previous experience in all areas. Completing these modules fosters teamwork and communication among the cohort in addition to expanding the experiences of each student. To date, ten Integrated Workshop modules have been developed and offered (listed in Table III). New modules are added each year, as new faculty become involved. In a given year, we offer a subset of this master list of modules.

IGPPEB seeks to be a holistic training program, which fully integrates research, teaching, learning, outreach and community engagement. For example, we encourage IGPPEB students to use Integrated Workshop module 10 to fabricate components for hands on science modules to be used in the Breakthrough New Haven summer program (see "IGPPEB Enrichment Activities Beyond the Core Courses"). For example, students are designing and building a modular car that is complete with accessories and a

TABLE II *Examples of Methods and Logic in Interdisciplinary Research discussion topics and papers*

Discussion topic	*Titles of papers discussed*
Mechanistic insight into motor proteins	"Myosin V Walks Hand-Over-Hand: Single Fluorophore Imaging with 1.5-nm Localization" [7] and "Kinesin Moves by an Asymmetric Hand-Over-Hand Mechanism"[8].
The role of signaling circuits in the regulation of biological processes and in establishing memory in biological systems	"A positive-feedback-based bistable 'memory module' thatgoverns a cell fate decision" [9] and "Bistability in cell signaling: How to make continuous processes discontinuous, and reversible processes irreversible" [10].
Nucleosome positioning and remodeling	"A genomic code for nucleosome positioning" [11] and "Dynamics of nucleosome remodeling by individual ACF complexes" [12]
The role of packing in protein cores—comparing experiment and theory	"Alternative packing arrangements in the hydrophobic core of lambda repressor" [13] "Tertiary templates for proteins—Use of packing criteria in the enumeration of allowed sequences for different structural classes" [14].
Using Fluorescence Correlation Spectroscopy to study complex biological processes in live zebrafish	"Fgf8 morphogen gradient forms by a source-sinkmechanism with freely diffusing molecules" [15] "Modular scanning FCS quantifies receptor-ligand interactions in living multicellular organisms"[16].
Conformational landscapes of Intrinsically Disordered Proteins	"Net charge per residue modulates conformational ensembles of intrinsically disordered proteins" [17] "Charge interactions can dominate the dimensions of intrinsically disordered proteins" [18].
The power of mathematical modeling in biology: cytokinesis and actin filament assembly	"Self-organization of actin filament orientation in thedendritic-nucleation/array-treadmilling model" [19] "Rapid Microtubule Self-Assembly Kinetics" [20]
How chromosome organization and genome architecture drive nuclear functions	"Effect of Chromosome Tethering on Nuclear Organization in Yeast" [21] "Cohesin-dependent globules and heterochromatin shape 3D genome architecture in S. pombe" [22].
Plasticity of the nucleus in disease and stem cells	"Physical plasticity of the nucleus in stem cell differentiation" [23] "Repetitive disruptions of the nuclear envelope invoke temporary loss of cellular compartmentalization in laminopathies" [24].

customizable track, to teach middle school students about friction, drag, inertia, and other physical principles in a hypothesis-driven manner.

Biological Physics

The goal of this course is to show the students how biological systems can be examined using the tools of statistical physics, including such topics as diffusion, allostery, Brownian ratchets, and kinetic proofreading. In many cases, students analyze and model experimental data using Monte Carlo and molecular dynamics simulations implemented in MATLAB. To incorporate peer learning, students are encouraged to work together on challenging homework sets.

Dynamical Systems in Biology

This course explores a variety of dynamical processes in biological systems. Topics include cell growth, spatial patterning, shape fluctuations, and the time-dependent dynamics of regulatory, signal-transduction, and neuronal networks. To highlight the importance of combining theory and experiment, simulations of these models are compared with wet-lab experimental data. Students are encouraged to work together on weekly exercises and use

TABLE III *Integrated workshop modules*

1) **"Bacterial Chemotaxis"**: Students track *E. coli* under a bright field microscope and record video footage of their motion. They analyze the data quantitatively, and extract statistics relevant to chemotaxis, including run length, run time, and tumble bias.
2) **"Single Molecule Super Resolution Microscopy: Sample Preparation to Data Analysis"**: Students prepare biological samples, image them, and process the data. They refine algorithms used in image analysis, optimize parameters associated with image acquisition, and test the feasibility of specific experimental setups. The combined results of many students who took this module have been published [26].
3) **"Forces Driving Cellular Motion: Skin Mechanics"**: Students use different types of microscopy, including traction force microscopy and differential interference contrast microscopy, to image keratinocytes and investigate how skin cells exert forces on their environment.
4) **"Analysis and Design of Protein Interfaces"**: Students develop their own computer codes to interrogate different features of protein structure. They employ the computational tools that they develop to assess the quality of protein structures and protein-protein interfaces.
5) **"Single Molecule Experiments: Measurement and Data Analysis"**: Students prepare biological samples, make measurements on them and analyze and interpret their data. To date, Tethered Particle Motion, optical tweezers and atomic force microscopy experiments have been conducted to study the accessibility, stability, and regulation of chromatin.
6) **"Managing Oxygen in Single Molecule Biochemistry"**: Students devise sample preparation strategies to minimize the effects of oxygen damage in single molecule force and fluorescence experiments. In the process, they learn about redox chemistry, sample preparation, and optical tweezers experiments.
7) **"Estimation of the Turnover of Endocytic Proteins Using a Single Molecule Strategy"**: Students prepare samples and measure the turnover rates of proteins in clathrin-mediated endocytosis, using high resolution fluorescence microscopy. They employ particle tracking, and analyze data in the context of mathematical models.
8) **"Optimization of a Microfluidic Device for Single-Cell Trapping without Surface Modifications"**: Students fabricate microfluidic devices and use them to perform live cell experiments. Based on their results, students make recommendations for device optimization for various applications.
9) **"Multi-scale Modeling of Biological Systems"**: Students simulate biological processes across length scales, from molecules to organs. They perform literature searches to obtain experimental data needed to build and validate mathematical models. They also identify new parameters that may be needed to improve the models.
10) **"3D printing: Design and Fabrication"**: Students use 3D printing and other resources available in Yale's Center for Engineering Innovation and Design, to design and make useful research tools (from proposals suggested by faculty and students) or items for outreach activities. To date, custom lab accessories that the IGPPEB students have made include laminal flow cells for microscopy studies, a 3D scanner capable of converting shapes of objects into digital structures, and a customizable bench-top centrifuge with modular components.

MATLAB to build mathematical models of biological systems.

Choosing a Research Group and Thesis Research

Students are exposed to different research groups through classes, research talks by students and faculty members, and the Integrated Workshop modules. In addition, all students complete one or more laboratory experiences during the first academic year, at the end of which they choose a mentor and research group for their thesis research. We encourage joint mentorship by IGPPEB faculty and that students have at least one IGPPEB faculty member on their thesis committee.

IGPPEB Enrichment Activities Beyond the Core Courses

Effective communication skills are of vital importance for success in essentially every career. A key theme of the IGPPEB is that students should develop the ability to communicate well with experts in ones' field, with scientists outside one's field, and with non-scientists.

To empower IGPPEB students to engage with all these constituencies, we have initiated several outreach activities.

Although not required, most IGPPEB students enthusiastically participate in these activities. The students benefit both intellectually in the planning and execution of an activity, and practically, as a "Broader Impacts" component of any grant and fellowship applications they submit. In addition, the program incorporates many opportunities for students to network with other scientists both at Yale and elsewhere.

Undergraduate Teaching

A strong teaching portfolio is increasingly important for scientists seeking academic careers. In addition, all IGPPEB students are expected to teach as part of their graduate education. A large body of research has demonstrated that traditional lectures both inadequately prepare undergraduate students for careers in the sciences and produce higher attrition among science majors, especially of women and under-represented minority groups [26]. A Scientific Teaching approach, that emphasizes active learning, a diversity of approaches, inclusivity, and assessment [27], does a better job of engaging undergraduate students and equipping them with skills to succeed in the sciences. With the goal of helping IGPPEB students become the vanguard of a new generation of highly effective scientific teachers, we encourage them to take Yale's Scientific Teaching class. The students learn many aspects of Scientific Teaching, including how to employ the most effective teaching methods, to create an inclusive classroom and to design and implement assessment tools.

Interactive Science Presentations for Elementary and Middle School Students

During the summer, elementary and middle school students from a local summer camp visit the Raymond and Beverly Sackler Institute at Yale, and IGPPEB students devise effective ways to explain their research to these students. The goals are to introduce children, in a fun and exciting way, to interesting scientific topics, to show them the diversity of "real scientists" and to pique their interest in STEM topics in general. IGPPEB students give a short presentation on their research and also devise and implement a relevant hands-on activity. Participation in such activities encourages IGPPEB students to develop creative teaching strategies and to practice communicating complex ideas in a clear and simplified fashion.

Breakthrough New Haven

IGPPEB students design hands on science modules for the summer session of Breakthrough New Haven, a program to prepare socioeconomically disadvantaged 7th and 8th grade students from New Haven public and parochial schools for success in high school. A module developed by an IGPPEB student combines electronics and computer science, teaching the basics of each while emphasizing their interdisciplinary nature. IGPPEB students, as part of the "3D Printing: Design and Fabrication" module in the Integrated Workshop, are currently developing a physics module using a modular 3D printed car and track system. The goal of this module is to teach classical mechanics in an exciting, hypothesis driven fashion. IGPPEB students are involved in all stages of the planning and implementation of these modules. They meet with the schoolteacher in charge to plan learning goals and the practicalities of offering a hands-on module. The IGPPEB students devise and test all components of the module, and then provide the module (with detailed instructions) to the teacher in charge and the high school teaching assistants who will work with the summer students. In addition to the creativity and practical planning required to devise and implement these modules, the entire process also strengthens IGPPEB students' communication skills. Successful modules are disseminated nationally via the Breakthrough Collaborative.

NSF Research Experiences for Undergraduates (REU) Site

The IGPPEB has included from the outset opportunities for undergraduates to perform summer research in IGPPEB laboratories. These efforts are now sustained by a National Science Foundation Research Experiences for Undergraduates (REU) Site program. We pay particular attention to recruiting students from under-represented groups and from predominantly undergraduate institutions. To avoid marginalization and to promote the best Yale and New Haven experiences, we include in the program two Yale undergraduate students, who are working in the labs of IGPPEB faculty. IGPPEB graduate students not only mentor REU students in laboratory research but also provide live feedback on the REU students' mid-program oral presentations. Feedback from graduate students in such a setting is less intimidating, and more effective, than faculty feedback. IGPPEB students also serve as judges for the final REU poster session. Not only are these interactions helpful to the REU students, they also make the IGPPEB graduate students more aware of what makes an effective talk or poster when presenting their own work. IGPPEB graduate students participate in several of the REU social activities, thus providing an opportunity for wide-ranging informal conversations.

Communicating Science to Non-scientists

To empower IGPPEB students to engage with non-scientists and thereby help increase public understanding of science, IGPPEB supports and encourages students to participate in a Short Course on Communicating Science to the Public. Robert Bazell, former Chief Science and Health Correspondent at NBC News developed this course and is the lead instructor. Students work on their public speaking skills, applying methods from theatre and improv. Guest lecturers include actors and directors and journalists who specialize in communicating science to the general public.

National Science Foundation Physics of Living Systems Student Research Network

In 2009 Yale was one of the founding members of the NSF funded Physics of Living Systems Student Research Network (PoLS SRN). This expanding network of domestic and international institutions brings together graduate students and faculty conducting research at the interface of physics and biology. Each summer an institution in the network hosts a 3–5 day meeting, where graduate students and faculty present ongoing research in talks and posters. The program also includes several informal networking opportunities for the students. Faculty from participating institutions and representatives from the NSF also share their experiences and brainstorm ideas for new initiatives in interdisciplinary research and graduate training. First-year IGPPEB students present posters based on their Integrated Workshop laboratory modules. In addition to building IGPPEB students' national research network, the inclusion of international institutions in the network introduces students to researchers from other countries and gives them a taste of the international nature of science.

Distinguished Speaker Series

We initiated an IGPPEB lecture series to bring distinguished speakers to Yale. In addition to attending the lectures, we also ensure that the speaker's schedule includes time with IGPPEB students, such as student-hosted lunches. We also encourage the students as a group to choose and host one speaker in this series each year. Recent presentations have included: "Bioimaging at the Nanoscale: Single-Molecule and Super-Resolution Fluorescence Microscopy" (Prof. Xiaowei Zhuang); "Mechanics and Dynamics of Cell Motility" (Prof. Julie Theriot); "How proteins fold, how they don't, and how to do it in a computer" (Prof. Ken Dill), "Motion Sensors, Orientation Sensors, and Object Segregation" (Prof. Jun Zhang); "Whose Responsibility Is It? The Need for Scientists to Talk About Science with Non-Scientists" (Prof. Thomas Baldwin); and "Printing Biomimetic Materials" (Prof. Jennifer Lewis).

Research in Progress Internal Seminar Series

This monthly seminar series serves to maintain cohesion of the IGPPEB and allows faculty and students to keep abreast of current research endeavors at Yale. Each session includes a catered lunch and two 30-min "research in progress" talks by IGPPEB students, postdocs or new faculty. The series is organized by two IGPPEB students from different home departments. The organizers make an effort to have pairs of speakers who will speak about different topics and approaches.

At the end of the academic year, this series hosts a special session for each second year student to give a 5-min flash talk about their thesis research. (In recent years, students have self-organized practice sessions for these talks.) We collect short, anonymous feedback on the substance and quality of all presentations, which we compile and share with the students. This exercise is particularly important because flash talks are becoming more common at national and international research conferences. Moreover, the ability to convey information in a concise and engaging manner is a critical and transferrable skill.

Effectiveness of the IGPPEB: Survey Results

We employed an anonymous student survey, including both quantitative and qualitative assessment, to determine to what extent the IGPPEB is achieving its goals (Fig. 2) and how well the program courses meet their learning objectives (Fig. 3).

Thirty of the 43 current IGPPEB students responded to the survey (70% response rate), with equal representation from the biological and physical sciences. Over 80% of respondents answered "yes" to 15 of 17 questions pertaining to the goals of the program, so we conclude that IGPPEB is achieving its goals (Fig. 2). These results are gratifying, but we are keenly aware that sustained effort is needed to maintain and continue to improve the program. Students are, for the most part, satisfied with the IGPPEB courses and believe that they have achieved their learning objectives. (Fig. 3 shows the survey and tabulated responses). Representative student responses to survey questions include: "As a physicist, I not only learned a lot of facts on biology, but also methods, principles, and ideas behind biology. Meanwhile, I gained a lot of experiences outside my field, and got to know professors and students in various disciplines. I had great experiences with people from different backgrounds, and attended exciting events on campus and in other universities." "[IGPPEB] definitely has helped keep me thinking of things on a mathematical side as well. I think this is really important because it is really easy to get bogged down in pure biology, while I think that integrating physics and modeling is really key in advancing in biology." "IGPPEB has supported me as I learn to communicate science effectively, both to other scientists in other disciplines and non-scientists. IGPPEB events and people have exposed me to a far greater range of research than I honestly would have sought out otherwise. I have learned about many techniques and analyses that I would have otherwise missed, and am excited about applying some to my own research in collaboration with someone I would not have met without the IGPPEB. Attending iPoLS in Munich was an amazing experience."

However, the results of the survey also drew our attention to weaknesses in the program. For example, although IGPPEB students considered the primer course Mathematical Methods in Biophysics to have met the learning objectives in probability and statistics, they did not consider that the learning objectives for differential equations, linear algebra and MATLAB proficiency had been met.

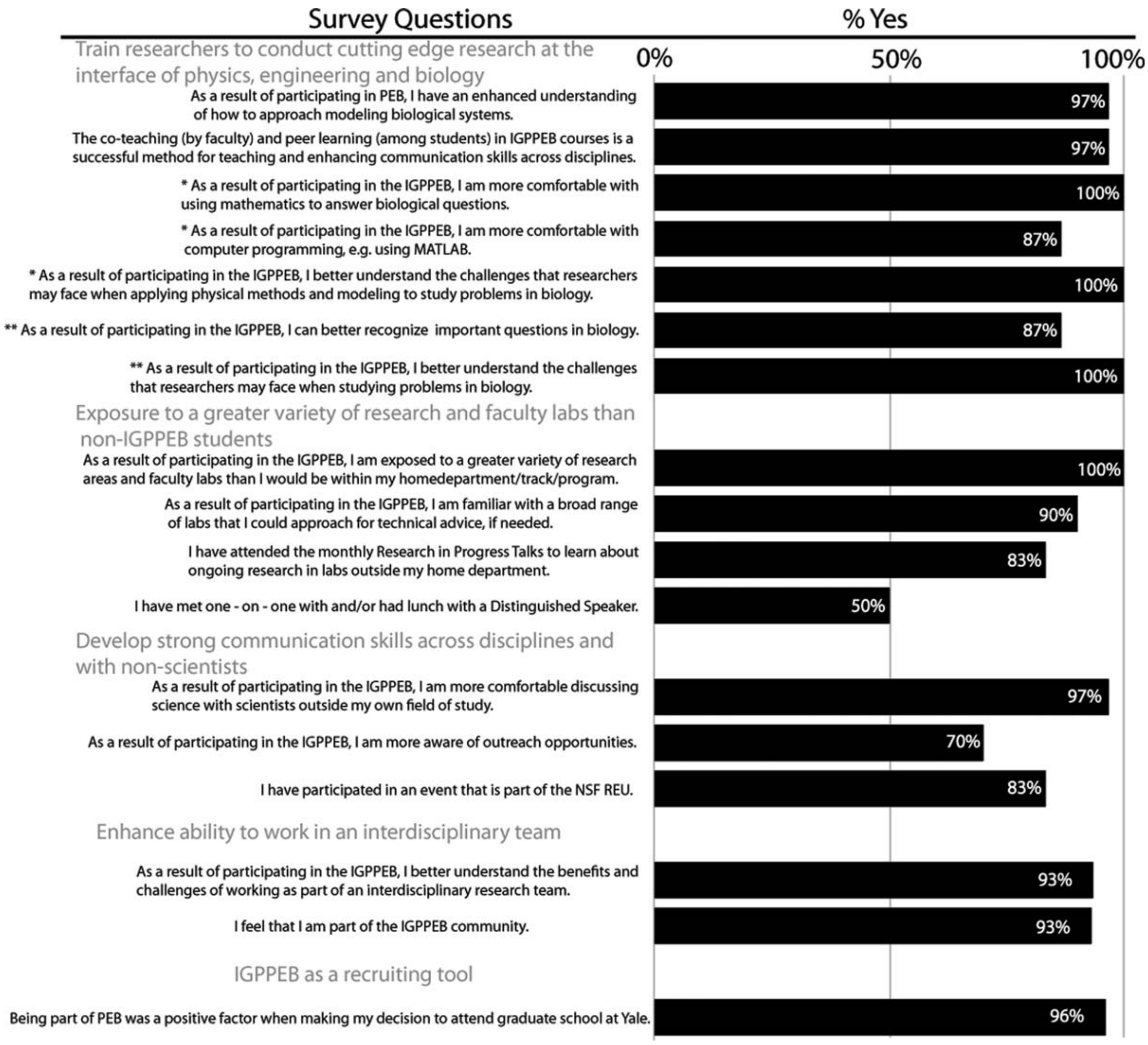

FIG 2 *Effectiveness of the IGPPEB in achieving its goals. Each goal (grey) is followed by a set of questions relating to that goal. Asterisks (*) indicate responses by students entering the IGPPEB through the biological science and double asterisks (**) indicate responses by students entering the IGPPEB through the physical sciences.*

IGPPEB faculty will modify the primer course Mathematical Methods in Biophysics based on the student feedback. However, because this material is vitally important and additional student comments revealed a wider need for further programming experience, we put in place an immediate response. IGPPEB sponsored two all-day programming workshops through Software Carpentry, a non-profit volunteer organization dedicated to teach researchers basic computing. The first of these focused on the Unix Shell, programming in Python, and version control, while the second focused on the Unix Shell and MATLAB. In addition to the trained instructors, senior IGPPEB students also contributed to the workshops by serving as teaching assistants and generating in-class problems sets using data acquired in IGPPEB laboratories. Instructors for the IGPPEB course Biological Physics obtained funding from Yale's competitive Associates in Teaching Program, which will be used to re-vamp the course, in particular, by incorporating a stand-alone MATLAB primer. Although by the strategies described, we have begun to remedy the deficiencies in teaching programming and applying quantitative methods, we have still not honed in on the best format and contents for instruction in these areas.

Establishing and Maintaining a Cohesive and Diverse Student Body

The IGPPEB seeks to create a diverse and cohesive student body. The structure of the courses and the variety of enrichment activities are designed to build cohesion and to instill a strong identification with the program that persists beyond the first year. The IGPPEB leadership embodies diversity, with an Executive Committee that is 43% women and faculty from under-represented groups. Thus, the Executive

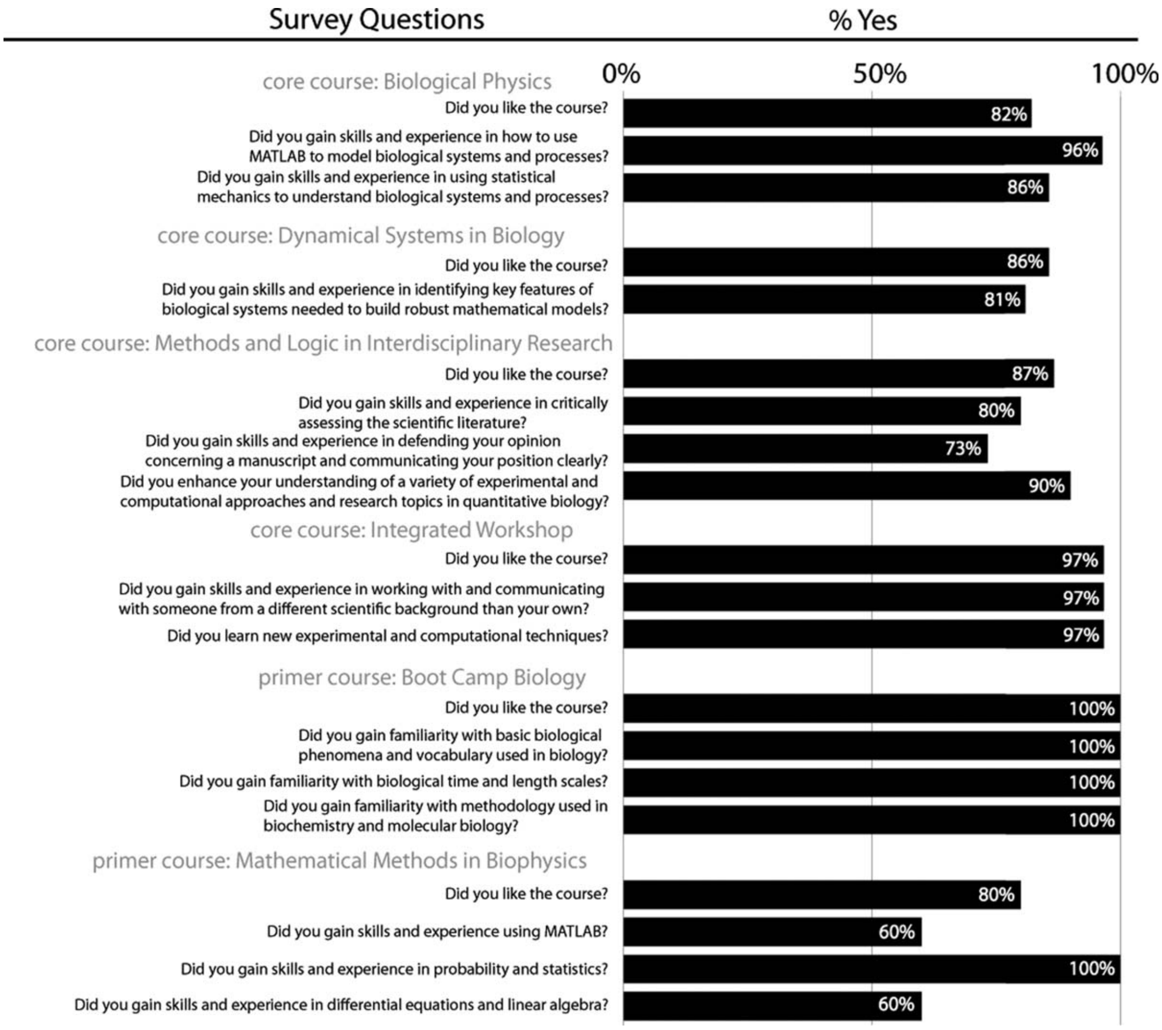

FIG 3 *Effectiveness of the IGPPEB core and primer courses in achieving the learning objectives. Course name (grey) is followed by a set of questions relating to the course (black).*

Committee sets the tone that diversity is integral to creating and preserving a vibrant and intellectually engaging atmosphere. IGPPEB faculty also works to recruit a diverse student body by attending ABRCMS and other minority-focused meetings and mentoring REU students. To date, 74% of the REU students have been female and/or from an underrepresented group, and to date two IGPPEB students were recruited via their participation in the REU program. Of current IGPPEB students 44% are women or from underrepresented groups.

Challenges Encountered in Setting up the Program and How we Met Them

Integration of IGPPEB with Home Program Curricula

A critical aspect of developing the interdisciplinary graduate training program was the efficient integration of the IGPPEB curriculum with the curricular requirements of the home programs. A key challenge was to avoid an increase in time to the PhD degree. The IGPPEB leadership worked with each home program to determine how best to mesh calendars and curricula. A key compromise was that some of the IGPPEB required courses count as home program elective courses.

Participation of their students in the IGPPEB has several advantages for the home programs. One is that the IGPPEB attracts students to the home programs, enhancing rather than competing with existing Ph.D. programs. Of survey respondents, 96% indicated that being part of the IGPPEB was a positive factor in their decision to attend graduate school at Yale (see Fig. 2). The IGPPEB also attracts strong students, as evidenced by the numbers who win external fellowships.

Continued communication between the IGPPEB and home programs has proven critical. The administrative structure, with each home program represented on the Executive Committee, facilitates timely reciprocal exchange of information. In addition, building robust ties between the Associate Director and the home program registrars and University assistant and associate deans has been vital in ensuring that programmatic changes are propagated through all appropriate departmental and university documents.

Differences in Curricular Requirements Among Home Programs

Each home program has different course requirements. For example, PhD students in Applied Physics have to complete two 4-month laboratory rotations and 10, semester-long courses, seven of which are specified. In contrast, PhD students in Molecular Biophysics and Biochemistry must complete three 2-month laboratory rotations and seven semester-long courses, two of which are specified and several have to fit within the program's core areas. Ideally, IGPPEB students would take all IGPPEB courses together as a class year to enhance cohesion and program identification among participants. However, because of the varied home program curricular requirements, this is not possible. Therefore, some of the IGPPEB students complete the IGPPEB curriculum in the first year, while others take two years.

Continuous Curriculum Development and Growth

The vitality of the IGPPEB program depends on continuous curriculum development, a high level of faculty participation, and incorporation of faculty new to Yale. The IGPPEB curriculum is structured so that it can easily incorporate new teaching faculty. Moreover, the courses vary in their levels of commitment from co-teaching a single session in Methods and Logic in Interdisciplinary Research to devising a new Integrated Workshop module to co-teaching a core course. Thus, teaching itself is an integral facet of maintaining a network of interdisciplinary researchers.

Remaining Challenges

Departmental Recognition of Interdisciplinary Teaching

At Yale University, Departments determine the teaching responsibilities of their faculty, and the home departments have varied in their recognition of teaching in the IGPPEB. Teaching in an IGPPEB course fulfills a Departmental teaching requirement in some departments, and receives partial or no credit in others. This issue is not yet resolved and may require higher-level administrative input.

Institutional Bureaucracy

Yale University is organized by departments, which themselves are organized into schools, including the School of Engineering and Applied Science, School of Medicine, and the Faculty of Arts and Sciences. In many cases, the infrastructure and bureaucracy is very firmly tied to these structures, requiring a substantial amount of work to establish a program or activity that not only crosses Departments but also Schools. An example we encountered was how best to allow applicants to indicate their interest in the IGPPEB within the confines of the existing graduate school application form. Another challenge was to determine the most effective way to recruit for IGPPEB, in partnership with the home programs. As graduate education evolves to best meet the needs of the scientific enterprise, an important aspect to consider will be how to create an academic culture that can readily accommodate new models of training future leaders in STEM.

Finding the Best Time to Offer the Integrated Workshop Hands-on Course

The Integrated Workshop is an important and effective component of the IGPPEB program. Identifying the best time for students to take such a course has been a topic of considerable discussion among IGPPEB faculty. Currently, students take it in the second half of the Spring semester, in place of a rotation (biology home programs) or Special Investigation (engineering and physics home programs). The benefit of this timing is that the students have some preparation, having taken IGPPEB primer courses (if needed) and the Methods and Logic in Interdisciplinary Research core course. A down side of this timing is that it is rather late in the student's first year, and it is at a time when pairs of students are taking several other courses required by the IGPPEB and home departments. An alternative strategy would be to offer an intensive version of the IW during the summer, prior to the start of the student's first academic semester. Advantages of this timing are that the course would facilitate IGPPEB student bonding at the start of the program; students would not be taking other courses, so synchronization of schedules would not be a problem; and it would be straightforward to interweave the contents of the primer courses with the hands-on laboratory modules, possibly eliminating the need for formal primer courses. A major disadvantage of this timing is that it requires all students to arrive on campus during the summer, 2 or 3 weeks before the start of the Fall semester. We are still seeking the optimal resolution of this issue.

Change Catalyzed by the IGPPEB on the Institutional Level

The IGPPEB program has catalyzed multiple changes at the institutional level. Most importantly, it has created a robust and extensive network of researchers that crosses the prior boundaries of Departments and Schools. The foundations of the network are the IGPPEB courses, which are taken by a wide range of students and taught by faculty that span both Departments and Schools at Yale. For example, the Methods and Logic in Interdisciplinary Research course is taught by the most departmentally diverse set of faculty of any course at Yale. IGPPEB activities also catalyze a network of students and faculty in new research associations. To quote a current IGPPEB student, "The broad set of students and faculty I interact with in IGPPEB makes a unique environment and introduces topics and research questions that I otherwise would not have encountered." IGPPEB students identify strongly with the program that lasts beyond the first year in graduate school. This is evidenced by 93% of IGPPEB survey respondents reporting being part of the IGPPEB community (Fig. 2). Finally, the IGPPEB is changing the climate and diversity of STEM research at Yale. The Executive Committee is comprised of 43% women and individuals from under-represented groups (URGs). This leadership sets the tone from the top, promulgating robust URG recruiting activities, a vibrant summer program for URG students, and outreach to local schools.

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