2002

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Repository Citation
S. Amador Kane, “An undergraduate biophysics pr ogram: curricular examples and lessons from a liberal arts context” Am. J. Phys. 70 , 581 (2002).

AMERICAN JOURNAL of PHYSICS

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Citation: Am. J. Phys. **70**, 581 (2002); doi: 10.1119/1.1473645
View online: http://dx.doi.org/10.1119/1.1473645
View Table of Contents: http://ajp.aapt.org/resource/1/AJPIAS/v70/i6
Published by the American Association of Physics Teachers

An undergraduate biophysics program: Curricular examples and lessons from a liberal arts context

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(Received 28 November 2001; accepted 26 February 2002)

The undergraduate concentration in biophysics at Haverford College is described, along with references to similar programs nationwide and reflections on the construction of sample curricula, administrative issues, and resources available for starting up related programs.
[DOI: 10.1119/1.1473645]

I. INTRODUCTION

In 1993 Haverford College instituted a formal program in biochemistry and biophysics.[1] Our goals in constructing such a program included the desire to serve students who found the traditional departmental boundaries within the natural sciences inadequate to describe the breadth of their interests. We found that many students were electing to leave physics because they were unaware of options for combining physics with ongoing study in biology and chemistry. In addition, an increasing number of professional physicists study problems directly related to, or inspired by, biological phenomena. We wished to bring into the physics curriculum these new and exciting research areas, as well as to encourage students to consider research careers in biological physics. Another goal was the need to prepare students for a variety of careers and graduate programs in medicine, biophysics and bioengineering. Within our department, this development was seen as part of a larger effort to acknowledge ongoing trends in physics employment and research, with interdisciplinary training becoming an increasingly important thread. At the same time, we have been developing concentrations in education (K–12) and computer science for physics majors.[2] We also provide detailed advising materials to majors interested in either industrial careers or post-baccalaureate study in engineering.[3]

It is easy to find indications that biophysics programs are addressing a national need. The utility of physics in biology and biomedicine has been well understood for over a century, but in the past decade this interplay has resulted in an explosion of new research and applications. The physical tools that already have proven so powerful in biology, such as electron microscopy, nuclear magnetic resonance, x-ray crystallography, and neutron diffraction, have been more recently dramatically supplemented by new techniques, such as scanning probe microscopies, laser tweezers, ultrafast laser spectroscopy, and computational methods. Harold Varmus, former director of the National Institutes of Health (NIH), has written about the potential for physics research to have a positive impact on biology and medicine in three crucial areas, noting the important role of physics in the early days of molecular biology.[4] Three areas where Varmus believes physicists' skills will be of special use are (1) physical and chemical techniques for determining the properties of single macromolecules and supramolecular complexes; (2) computational methods for interpreting complex data sets, such as analyzing genetic databases, finding genes, and analyzing the results of DNA and protein microarray experiments; and (3) the study of cell signaling pathways, such as those that control the cell cycle and regulate gene expression. The NIH recently has created a Bioengineering Consortium (BECON) to fund research in these areas, among others. A recent editorial in *Nature* has seconded this need for new approaches to entirely new fields of biology created in the last decade, such as bioinformatics, while pointing out the hurdles often faced by practitioners straddling two fields and the difficulties in finding scientists trained to think about such problems.[5] Research universities are increasingly forming multidisciplinary research centers to address problems in biophysical chemistry, biophysics, neuroscience, bioengineering, and computational biology.[6] Meanwhile, prominent biologists are beginning to reassess the skills required for biological and biomedical research, and how this need should impact the design of biology curricula.[7] We see the role of undergraduate biophysics programs as addressing these needs in a twofold manner: they encourage physics majors to learn more about biology, while stimulating biology and chemistry majors to learn more physics while seeing more clearly the relationship of physics to their own fields.

At Haverford College, a concentration is a program of study taken in conjunction with a specific major (or majors) and requiring the same number of courses as a minor in other institutions; unlike a minor, there necessarily is an integral relationship between the major and concentration fields of study. Our biophysics program was developed as a concentration to recognize the fact that students pursue the curriculum from host departments in the natural sciences: biology or physics for the biophysics concentration, or biology, physics, or chemistry for the related biochemistry concentration.

In this article, I will focus exclusively on the biophysics programs, and the ways in which our formulation of these curricula involve collaborations between physics and its sister departments in the natural sciences. For comparison, Robert I. Boughton has recently described a different interdisciplinary approach that allows undergraduates to study materials science in a liberal arts setting.[8] The strong emphasis on molecular biology and biochemistry in our biology and chemistry programs had a large role in the selection of an emphasis on molecular biophysics. Other obvious emphases for a biophysics program, such as neuroscience, mathematical biology, bioengineering, or medical physics are of great interest and might be more feasible and appropriate in other settings.

The biophysics concentration is part of a larger effort that we have undertaken to change other aspects of the physics curriculum and to make connections between physics and the life sciences in existing contexts. For example, our introductory courses now include more medical and life sciences applications in the sections most frequented by premedical students. Many examples can be found in introductory physics textbooks that emphasize life science and medical applications.[9] Possible topics include (their relation to the standard curriculum is indicated in parentheses): laser tweezers and mechanical properties of biopolymers (springs and Hooke's law); medical ultrasound imaging (waves, sound, and the Doppler effect); nerve conduction, magnetic resonance imaging and nuclear magnetic resonance (electricity and magnetism); x-ray diffraction, applications of fiber optics in medicine, and laser surgery (optics, interference, and diffraction); and radiation biophysics, x-ray imaging, and radiation therapy (modern physics). We also include some biological physics in upper-level courses such as statistical physics. Examples include diffusion and random walks, especially as they concern polymer physics and diffusion in biological systems; DNA zipper models as a simple explanation of DNA melting; errors in DNA duplication; the binding of oxygen and carbon monoxide to hemoglobin; molecular mechanics and molecular dynamics; and the relationship between phase transitions and neural networks. Discussions, problems, and worked examples relating to many of these topics can be found in recent textbooks on statistical physics and biophysical chemistry.[10]

II. THE CONCENTRATION CURRICULUM

All students doing either a biochemistry or biophysics program must complete a sequence of core courses in the three host departments, followed by specified interdisciplinary upper-level coursework beyond their major requirements. Our regular reviews of molecular biophysics programs at other institutions have found that their structure is essentially the same as ours, with minor exceptions. Examples of similar programs can be found using the Biophysical Society's on-line listing of undergraduate and graduate programs in biophysics with e-mail addresses of the contact persons, and direct links to the programs' web sites.[11]

Our biophysics and biochemistry concentration core curriculum is as follows:

- Biology 200a-200b (a full year of molecular and cellular biology).
- Biology 300a or b (one semester of junior-level biology laboratory; one semester focuses on the biochemistry of proteins and nucleic acids and the other on various forms of microscopy and immunological methods).
- Chemistry 100-101 (general chemistry) and 220a (organic chemistry I).
- Mathematics 114 (calculus II), 120 (accelerated calculus) or 121 (calculus III). (This requirement ensures students have had the equivalent of one year of college calculus.)
- Physics 101-102 or 105-106 (a full year of introductory physics with calculus; the two sequences emphasize, respectively, applications in the life sciences or physical sciences).
- Biology 303h (structure and function of macromolecules; a half-semester course) and one other advanced half-semester course selected from Biology 301d (genetics), 304g (biochemistry: metabolic basis of disease), or 306g (inter- and intracellular communication).
- Two semesters of research on an appropriate topic of biochemical or biophysical interest in any of the three participating departments. The major department and the concentration coordinating committee must approve the research.

Beyond this foundation, students must take courses to satisfy their major requirements and additional advanced interdisciplinary coursework. For physics majors, the remaining requirement for the biophysics area of concentration is one upper-level biophysics course, either Physics 320b (introduction to biophysics) or 230b (medical physics). Table I shows a possible four-year curriculum for a physics major with a biophysics concentration.

At Haverford College, the physics major presently requires six upper-level physics courses beyond the basic introductory and sophomore sequence, plus Mathematics 204 (differential equations). These courses must include an advanced laboratory course and three core physics courses selected from advanced quantum mechanics, statistical physics, advanced classical mechanics, and advanced electromagnetism and modern optics. Biophysics concentrators can count biophysics (Physics 230 or 320) and one research tutorial toward the remaining two requirements. Because of this overlap, the number of additional courses required is reduced to five semesters plus one extra semester of research. Nevertheless, the course load for physics majors electing this program remains heavy and challenging to coordinate. Most students opting to formally elect the concentration often have entered college at an advanced level in physics, mathematics, or chemistry, and thus are able to reduce the total number of required courses. (It should be noted as well that physics majors interested in biology, but not concentrating in biophysics, may petition the department to count upper-level coursework in another natural science department in lieu of up to two upper-level physics courses.)

The required upper-level biology courses deserve some attention. Although the inclusion of courses on protein structure and function, genetics and metabolic biochemistry might seem obvious, cell signaling (Biology 306) is less so. The latter has been included as an option in the belief that this area of biology both fills a fundamental place in current research, and is likely to play an increasing role in biophysics, as underscored, for example, by Varmus.[4]

This selection of courses represents the minimum requirements students must complete. Students can also choose to take advanced seminars on bioinformatics, cell motility, programmed cell death, protein design, bioinorganic chemistry, and biophysical spectroscopy. To obtain the best preparation for graduate study in molecular biophysics, students are advised to take a full year of organic and physical chemistry and additional courses in biology, and are encouraged to take additional courses in physics and mathematics if they plan to continue on to graduate study in physics.

Students also may elect to pursue the biophysics concentration with a biology major, in which case the core requirements are the same, but the remaining requirements differ:

- Mathematics 121 (calculus) and 204 (differential equations). This requirement ensures that students have the same minimum mathematics background as physics majors.
- Physics 213 (waves and optics) and 214 (introduction to quantum mechanics) plus the half-credit sophomore-level laboratory course Physics 211f (laboratory in electronics and waves).

Table I. Sample curriculum for a physics major with a biophysics concentration. This schedule assumes the student enters with the equivalent of college general chemistry.

Year One Fall	**Year One Spring**
Physics 101 or 105 (introductory physics)	Physics 102 or 106 (introductory physics)
Math 113, 120, or 215 (calculus)	Math 114, 121, or 216 (calculus)
Chemistry 220a (organic chemistry I)	(Social Science/Humanities Distribution)
Freshman English	(Social Science/Humanities Distribution)
Year Two Fall	**Year Two Spring**
Physics 213 (waves and optics)	Physics 214 (introduction to quantum mechanics)
Physics 211f (electronics and waves laboratory) 1/2 credit	Physics 212i (modern physics laboratory) 1/2 credit
Biology 200a (cell structure and function)	Biology 200b (cell structure and function)
Foreign Language Requirement	Math 204 (differential equations)
	Foreign Language Requirement
Year Three Fall	**Year Three Spring**
Physics 303 (statistical physics)	Physics 320b (introduction to biophysics)
Physics 326 (advanced physics laboratory)	Biology 300a or b (biology advanced laboratory)
(Social Science/Humanities Distribution)	(Social Science/Humanities Distribution)
Elective	Elective
Year Four Fall	**Year Four Spring**
Research tutorial for credit	Research tutorial for credit
Physics 308 (advanced classical mechanics)	Physics 302 (advanced quantum mechanics)
Elective	Biology 303 (protein structure and function)/304 (biochemistry: metabolic basis of disease)
Elective	
Senior Seminar 1/2 credit	Senior Seminar 1/2 credit

- Chemistry 304 (physical chemistry I) or Physics 303 (statistical physics).
- One semester of advanced physics laboratory, such as Physics 326 (advanced physics laboratory) or Physics 316 (electronic instrumentation and computers).
- Physics 320b (introduction to biophysics) or 230b (medical physics).

This curriculum represents a substantial commitment beyond the regular biology major, both in the number of required physics and chemistry courses as well as in the commitment to a specific curriculum within biology. Biology majors may count upper-level physics courses taken for the concentration in lieu of a second semester of advanced biology laboratory and one of their required senior-level advanced biology courses.

Two upper-level biophysics courses are offered within the physics department to give concentrators and other majors a more in-depth feeling for topics of current interest in biophysics. Recent syllabi, readings, and assignments are available on-line.[12] Readings have generally included selections from the research literature, in addition to selected chapters from biophysics texts,[13] including several recent collections of articles.[14] The concentration also maintains a listing of web sites for biophysics courses at other institutions and other on-line resources.[15] Physics 320b (introduction to biophysics) has been taught as a special topics course, with special attention paid to topics of broad molecular biophysical significance. The topics covered vary widely, but include the following.

- Experimental determinations of protein, DNA, and other biopolymer structure and dynamics by such techniques as x-ray and neutron diffraction, nuclear magnetic resonance, scanning probe microscopy, electron microscopy, and spectroscopic and optical trapping methods.
- Basic topics in biophysical chemistry, such as intermolecular forces and interactions, electrostatic screening, and the hydrophobic effect.
- Theoretical models of biopolymer structure: polymer chain statistics and the physics of helix-coil transitions; molecular mechanics and molecular dynamics; binary models of protein folding; statistical sequence-database-based models for predicting protein structure; and continuum rod models of biopolymers.[16]
- Biomembranes and lipid phase behavior, including a discussion of experimental methods as well as self-assembly and self-organization in general.[17]
- Single molecule manipulation and measurements in molecular biophysics, with attention paid to their use in enzymology, the study of molecular motors, and laser tweezer and atomic force microscopy characterization of biopolymer mechanical properties.
- Bioinformatics and biosensors, including gene-finding algorithms, search engines for genetic databases, and DNA and protein microarrays.[18]

In its most recent implementation, this course focused on both biological physics and such soft matter physics topics as polymers, membranes, gels, micelles, and liquid crystals. This effort has been greatly enhanced by the recent publication of several useful textbooks on soft matter physics.[19] Assignments consist of biweekly problem sets, a midterm and final exam, and a final term paper.

Physics 230b (medical physics) has focused on the science of modern medical imaging technologies and other applications of physics in medicine. Topics covered include diagnostic x-ray imaging, ultrasound imaging, nuclear medicine imaging techniques, computed tomography (CT), positron emission tomography (PET), magnetoencephalography (MEG), and magnetic resonance imaging (MRI), as well as laser surgery and radiation therapy. Each topic is approached from a highly interdisciplinary perspective, through consideration of topics ranging from the physics of ionizing radiation and the biology of cancer to computational techniques for image reconstruction. Specific medical applications discussed include mammography, screening for osteoporosis, applications of PET, MRI, and MEG brain scans in neuroscience research and neurology, obstetrical ultrasound imaging, the development of cutting-edge optical tomographic imaging techniques, and the use of imaging techniques in cancer radiation therapy planning.

Each topic includes an investigation of the basic science underlying the technique chosen, the instrumentation and imaging processing techniques utilized, and applications of each technique in either clinical settings or biomedical research. Guest speakers describe their use of these techniques in their research or clinical work, and we have arranged occasional field trips to area hospitals to see the techniques in action. Assignments include biweekly problem sets, two term papers, and several in-class group presentations. Readings include selected articles from the medical literature as well as assigned readings in several medical physics textbooks.[20]

Both courses' prerequisites have been kept to a minimum to accommodate junior and senior biology and chemistry majors. Students can take either course after having completed one year of molecular and cellular biology (Biology 200), and either Physics 214 (introduction to quantum mechanics) or one semester of physical chemistry. This requirement in effect limits enrollment to junior and senior physics, biology, and chemistry majors with adequate physics and biochemistry backgrounds. The student audience has been approximately equally distributed among physics, biology, and chemistry majors, including physics majors wishing to obtain a one-course exposure to biophysics. (The latter may enroll if they agree to do additional background readings in a molecular biology textbook.[21])

III. THE ROLE OF UNDERGRADUATE RESEARCH IN THE CONCENTRATION

The research requirements for the concentration are heavier than those for the physics major. Although our department requires a senior thesis for the major, there is no official requirement for research during the academic year. This flexibility allows some students to elect to write papers based on library research of their own choosing, or to write a senior thesis based on research performed during the summer before their senior year. The requirement of two semesters of research for the concentration was designed to ensure a depth of research participation that would enable the student to synthesize knowledge gained from the three natural sciences into a unified whole. Topics pursued in this context have included applications of laser tweezers in biology, biophysical tools for studying problems in immunology, protein design, and the use of atomic force microscopy to study DNA structure.

We have also worked to make available summer and academic year research opportunities for our majors. Students interested in the concentration are encouraged to apply for research assistanceships sponsored by the Howard Hughes Medical Institute (HHMI) and the Beckman Foundation, as well as faculty research grants and internal college sources of funding for student research. The associated faculty also encourage students to apply for summer research positions off campus.

IV. STUDENT PARTICIPATION

Statistics within our own department have indicated that, over the period 1992–2001, the proportion of students pursuing post-baccalaureate study or a career in biological sciences or biomedicine (17%) slightly exceeded that entering physics graduate school (19 vs 15 out of 111 majors in total). Many of these students graduated with a biophysics concentration, but a greater number came to an interest in biophysics later in their undergraduate careers, and therefore completed only a fraction of the introductory-level courses. For example, during this same period, nine students have elected the concentration, while an equal number have taken the majority of the courses required but stopped one or two courses short of a complete program.[22] Thus, the concentration often serves as an advising framework for adding appropriate biology and chemistry courses to a standard physics major. Students graduating with the concentration designation have pursued a variety of careers, ranging from bioengineering, M.D./Ph.D. programs, bioinformatics, and biophysics graduate school.

HHMI also sponsors a Minority Science Scholars program at Haverford College administered by a biology faculty member, and this resource has proven instrumental in providing early intervention for students at risk. Minority students electing to participate in this program can take advantage of peer tutoring programs, intensive faculty mentoring partnerships, summer and academic year research opportunities (tied to work study requirements during the academic year), and support in applying to graduate schools and jobs.[23] In part as a result of this program's success, the numbers of concentrators from minority groups have been substantial. In the decade since its inception, three of the nine biophysics concentrators and twenty of the seventy-four biochemistry concentrators have been minority students. For comparison, over the ten-year period 1992–2001, the proportion of physics and/or astronomy majors who were members of minorities was 10% (11/111). During the same period, approximately the same proportion of physics majors were women (12/111), with approximately half interested in astronomy, but none were biophysics concentrators. Thus, although we are encouraged by the level of participation by minority students, we are concerned that women are not entering the program in significant numbers in spite of the roughly equal representation of male and female students in biology and biochemistry programs on campus.

V. ORGANIZATIONAL ISSUES

Of course, such an interdisciplinary program naturally creates the need for new organizational entities within the academic institution, as well as new ways of evaluating junior faculty. This topic has been ably summarized in an earlier article.[24] We have dealt with these issues by having our biochemistry and biophysics concentration program administered by a coordinating committee composed of one physics faculty member and two representatives each from biology and chemistry. The concentration coordinator (chair) is a three-year position which rotates through the three parent departments. Decisions about the program are made in conjunction with the departments most affected, with the coordinating committee reviewing and recording decisions for consistency. For example, the choice of laboratory requirements for biology majors concentrating in biophysics is made in cooperation with the physics department, then approved by both the department and concentration. Other topics considered by the coordinating committee include allowed course substitutions, changes to the official plans of study, and future directions for the program. The concentration coordinator is also responsible for checking course time conflicts and making sure an appropriate slate of courses is always available for concentrators, both nontrivial issues when coordinating courses among three departments. Finally, the coordinating committee serves an important advisory role in the hiring of new natural science faculty in fields related to the concentration. Because undergraduate research is such an important factor in the concentration, two members of the committee are designated to review and comment on each faculty job candidate's teaching interests and research, and their relationship to the biophysics and biochemistry program.

VI. INTERNET RESOURCES

Many national organizations and educational institutions now provide valuable on-line resources for teaching biophysics. The following survey is meant to highlight only a sampling of these. One important resource is the American Physical Society (APS) Division of Biological Physics. This division, which holds its regular meetings as part of the annual APS March meeting, maintains a useful web site with listings for journals that publish biophysics, and listings of graduate programs in biophysics.[25] The web site for the Biophysical Society and related societies can be accessed directly or through the parent organization, the Federation of American Societies for Experimental Biology (FASEB).[26] The site contains a wealth of useful links for teaching, including the *On-Line Biophysics Textbook*, a collection of reprints from *Biophysical Journal* on the topic of teaching biophysics, as well monographs on various topics, and the Protein Society's Teaching Tools.[27]

VII. CONCLUSION

Although we strongly believe that a physics major is in itself an excellent preparation for a variety of careers, and we wish our majors to remain keenly aware of the excitement and progress in many areas of current physics research, we have found the addition of a biophysics program to be both feasible and attractive to many of our majors. While such a program requires high levels of cooperation between natural science departments, administrative structures can be created to deal with these issues. These programs have had the added benefit of creating additional faculty and student dialogue between the natural sciences in ways that have benefited our science programs overall. Future directions include the development of integrated projects to be shared between the advanced laboratory courses for biology, chemistry, and physics, and discussions about the structure of our first-year science curricula.

ACKNOWLEDGMENTS

Much of the support for the course and faculty development for these programs came from a series of grants from the Undergraduate Biological Sciences Education Initiative of the Howard Hughes Medical Institute. The creation and administration of these programs has involved many individuals, most notably members of the concentration coordinating committee: Karin Akerfeldt, Lois Banta, Frances Blase, Julio de Paula, Robert Fairman, Kate Heston, Karl Johnson, Slavica Matacic, Philip Meneely, Judith Owen, Jennifer Punt, Mel Santer, Robert Scarrow, Claude Wintner, and the late Ariel Loewy. I would also like to express my gratitude for the patience and support of my colleagues in our physics department, including Stephen Boughn, Jerry Gollub, Bruce Partridge, Lyle Roelofs, and Walter Smith.

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[1]The concentration's Web site at Haverford College is at http://www.haverford.edu/biochem-biophys/; the physics department's commentary on the program for physics majors is at http://www.haverford.edu/biochem-biophys/BioPhysics.PhysicsMajors.html.

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[3]See http://www.haverford.edu/physics-astro/engineering.html.

[4]H. Varmus, ''The impact of physics on biology and medicine,'' APS News **August/September**, 8 (1999).

[5]''Can physics deliver another biological revolution?,'' editorial, Nature (London) **397**, 89 (1999).

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[11]See the URL http://www.biophysics.org/products/programs.htm.

[12]See listings for Physics 320b and 230b at http://www.haverford.edu/physics-astro/course_materials/physcourses.html.

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[23] See http://www.haverford.edu/msp/welcome.html.
[24] S. M. Gruner, J. S. Langer, P. Nelson, and V. Vogel, ''What future will we choose for physics?,'' Phys. Today **48**, 25–30 (1995).
[25] See http://www.aps.org/DBP.
[26] For the Biophysical Society, see http://www.biophysics.org. For FASEB, see http://www.faseb.org/.
[27] The Biophysical Society's Online Biophysics Textbook is located at http://www.biophysics.org/btol/, while the Protein Society's Teaching Tools are at http://www.faseb.org/protein/.

LEARNING CONCEPTS

There is no automatic connection between the transmission model of education, and authoritarian, nonengaging, pedagogy. Just as there are many ways to skin a cat, so, too, there are many ways to teach something. But at the heart of science are concepts, and these need to be understood first. Scientific concepts are social or constructed. Students do not discover, much less construct, what *momentum, power, acceleration, valency, force, mass, weight, oxidation*, and so on mean: They *learn* what these terms mean. They may learn more or less badly depending on how prepared they are and how well the concepts are presented, and they have to put effort into their learning, but all of this is a long way from students constructing their own definitions of scientific concepts.

Michael R. Matthews, *Time for Science Education: How Teaching the History and Philosophy of Pendulum Motion Can Contribute to Science Literacy* (Kluwer Academic/Plenum Publishers, New York, NY, 2000), p. 280.

Submitted by Alan J. DeWeerd.