Education and Infrastructure

Biological physics and materials is an emerging field, overlapping but distinct from biophysics, quantitative biology, theoretical biology, and biomathematics. It has not only a distinct research identity, but also an educational identity that offers a conceptual base useful to other disciplines. It is useful to articulate a tentative consensus about what characterizes the theoretical branch of this field. Certainly, the activities listed below are not unique to biological physics and materials, and not all biological physics/materials researchers will subscribe to all of them. Nevertheless, we believe that an overall pattern emerges that is distinct from existing disciplines (in their current form). Theory in biological physics and materials:

- *seeks to apply physical principles, and the corresponding mathematical, engineering and computational tools, to biological systems. Reciprocally, we seek to extract new physical principles, and even new kinds of questions, from biological systems.*
- *develops quantitative models based on identifiable principles, and tests them on experimental data.*
- *seeks models that explain experiments of biological interest, yet are simple enough to be interpretable and to generalize, including to non-biological materials.*
- *seeks models that form connections between apparently disparate phenomena. To this end, we ask students to acquire a broad background, not just that subset known to be relevant to a particular project.*

While the approaches outlined above are certainly not always the best way to understand biological systems, they offer pathways for discovering new organizing principles, novel ways to find relevant patterns in data, and can lead to productive new questions.

Past Successes

Biological physics continues to expand rapidly, as evidenced by the growth of the Division of Biological Physics of the American Physical Society, whose membership has grown nearly 10% annually for several years. Contributed talks at the March meeting of the APS rose nearly 40% this past year alone. A considerable number of theorists supported by the DMR at the NSF have partial or fully migrated to biological physics in the past few years. Such extraordinary growth in this interdisciplinary field at the boundaries between physics, chemistry, biology, and mathematics presents unique challenges for students and faculty, and has brought to the fore important infrastructure and education issues which universities and funding agencies are now struggling to address. Some recent efforts at nurturing the development of theoretical biological physics have included the following:

- *NSF-sponsored Integrative Graduate Education and Research Traineeship (IGERT) programs, which are training a new generation of students in the physical, mathematical, and life sciences in an interdisciplinary manner.*
- *Dedicated NSF-sponsored centers, such as The Center for Theoretical Biological Physics at UCSD – a Physics Frontier Center – which has established a large scale biological physics research program at UCSD.*
- *NSF-sponsored theoretical physics centers, such as Kavli Institute for Theoretical Physics* (UCSB) and the *Aspen Center for Physics* - *which have run workshops on biological physics. These programs introduce problems in biology to physicists and build*

bridges to the biology community. They have been important in building up the biological physics community and in defining the subject of biological physics.

- *Several condensed-matter and materials theorists are writing or have written new biological physics textbooks; some with NSF support.*
- *Workshops for young scientists (the NSF-DMR Workshops on Opportunities in Materials Theory, the APS Topical Conference on Opportunities in Biology for Physicists, and the NSF-DMR Boulder Summer School in Condensed Matter Physics) which highlight research opportunities for theorists in biological physics and materials.*
- *The listing of Physical Review E and Physical Review Letters in Medline, making the biological physics literature accessible to researchers in the biology community.*

These efforts constitute a significant start, but there remain important challenges for the future. These range from how best to train students and postdoctoral researchers who will enter biological physics from within physics, to how best to meet the needs of life science students for appropriate grounding in physics (as outlined in the National Academy Report BIO2010), to the need to foster communication between researchers in those disparate fields.

Recommendations

Careers in Biological Physics and Materials

Physics departments have recently begun to incorporate biological physics as a well-defined subfield, alongside more established fields like condensed matter physics, high energy physics etc. There is a very pronounced shortage of individuals trained in both the theoretical methods of the hard sciences and the language and methods of biology, to build this subfield. The shortage is evidenced, for example, by the small size of the applicant pool relative to the number of positions available, and the difficulty of hiring postdoctoral research associates trained in biological physics. Below, we outline measures that can be taken to alleviate this shortage. For clarity, we subdivide them according to level of education and professional position. However, several of the measures, including the establishment of regional research and training centers, would benefit training in biological physics and materials at all levels.

High school: Students contemplating university studies do not always hear about the excitement within biology and biological physics, and that it is becoming possible to study aspects of quantitative biology in a physics context. To them, and to their parents, “physicist” sounds a lot like “professional poet.” In contrast, “chemist” or “engineer” immediately conjures up images of a real career. We need to work on our public image and the NSF can continue to help by supporting university-based summer programs for high school and undergraduate students. Many of our institutions already have such programs, but they are often hindered by uncertain funding and institutional commitment. Here the message is that students who enjoy mathematics and physics can apply these skills in biology and that this includes biological physics. The fact that parts of biology are now quantitative, and that physical and mathematical principles apply here, as well as in the other sciences, needs to be emphasized.

Undergraduate**:** Educational development must begin with innovative courses – see the “Curriculum” section below. As discussed there, we recommend that the NSF act to support the development of new instructional materials and other resources for instructors. NSF already supports undergraduate-level training in several ways, for example, with the REU program, support for undergraduate participation in sponsored research, and related activities. We recommend that the NSF continue to strongly support such programs.

***Graduate*:** Institutions such as the Boulder summer school, the Center for Theoretical Biological Physics at UCSD, and the Theoretical and Computational Biophysics summer school held at University of Illinois, provide an entry point into biological physics and materials. We strongly support mechanisms to expand the availability of such programs. An effective way to do this would be to set up regional research and training centers at larger universities with good facilities and faculty in biological physics. They could share this expertise with a larger regional group of universities, probably mainly during the summer months. This would be a transitional arrangement, over say a decade, until more universities establish significant, self-sustaining, programs in biological physics. The regional centers could offer courses to physicists at the graduate and postdoctoral level who need to get the basics of biology, with a distinct physics emphasis, in order to start research in biological physics. Chemistry is in a strategic position, midway between physics and biology, and some basic training is useful, particularly in the study of biomolecules. Since theoretical students should have opportunities for experimental experience as well as theory, laboratory-technique training analogous to that currently offered in the Woods Hole Marine Biological Laboratory program, could also be offered at these centers. Summer support from the NSF could be provided for faculty from the region to teach at these schools, and for students from the region to attend.

The NSF can also help to support the increasing number of graduate students studying biological and materials physics by funding graduate research fellowships in this area. These could, for example, be special fellowships targeted to biological physics, with modest travel and research support, including support for visits to external laboratories.

***Postdoctoral*:** Switching from physics to biology-oriented research during the postdoctoral stage of a career is a common path towards biological physics. Funding of biological physics projects that allow for the hiring of a postdoctoral researcher would provide natural support for this career path, as biological physics Principal Investigators readily employ postdoctoral researchers with backgrounds in physics and minimal explicit experience with biology. Thus, we recommend increased funding for postdoctoral fellowships supporting transitions into biological physics. We also recommend that the duration of such postdoctoral appointments be extended to three years to facilitate this transition to interdisciplinary research. We also note that the types of summer training programs discussed above for graduate students, and the opportunities available at regional research and training centers, would also be very helpful for postdoctoral researchers.

***Faculty*:** Extended workshops in biological physics at the Center for Theoretical Biological Physics at UCSD, the Kavli Institute for Theoretical Physics in UCSB and the Aspen Center for Physics have had a significant impact on many careers, enabling a transition from a mere interest in biology to active research in biological physics. We endorse NSF support for biological physics in such programs. Physics/Biology workshops however have an intrinsically different structure from the traditional theoretical physics programs at these institutions (e.g.

involve large number of short term biologists/experimentalists as visitors) and require additional and specific support. These workshops should be expanded to the new regional research and training centers proposed here, and could naturally cycle through different subjects of biological physics, ranging from biomolecules, molecular machines and assemblies to biological networks, bioinformatics and ecology.

An expansion of NSF funding for individual research grants for theory in biological physics and materials would increase the number of researchers entering the field, and we strongly support such an expansion. Sabbatical visits to institutions with active biological physics or extensive biology programs are also very important in enabling a change of scientific direction. Existing opportunities include the career-switch sabbatical support offered by NIH, and, on a smaller scale, by the Research Corporation. We encourage the NSF to build on and expand such efforts.

Community-Building**:** Workshops, schools, and centers such as those discussed above provide effective means to create and define the biological physics community at all levels. As the availability of these resources is expanded, the following goals should be kept in mind:

- *bring physicists and biologists together*
- *define important problems of common interest for biologists and physicists*
- *provide a forum and environment to nurture innovative new approaches to biology that address the fundamental issues of living matter*
- *establish interdisciplinary (and theory/experiment) collaborations*
- *provide education in biological problems for graduate, postdoctoral and more senior level physics researchers, and education in quantitative methods and physics approaches for biologists*

Funding Mechanisms

The interest shown by condensed-matter and materials theorists in contemporary problems in biology and biological materials has been documented in the preceding sections. The NSF has been far-sighted in its support of these developments. NSF initiatives such as the NSF DMS/NIH collaboration have spurred innovation by specifically pairing mathematicians with biologists. We strongly urge the creation of a similar program linking NSF DMR with NIH. Such programs help interface theorists with the vast variety of experimental work supported by NIH. Two great advantages of this funding model for many biological physicists are the added flexibility given by joint NSF/NIH panels which can ensure that biological physicists are proportionally represented, and that innovative embryonic areas have increased chances of attracting funding. One promising avenue for joint NSF/NIH programs is the creation of training grants at the graduate and postdoctoral level which would require the participation of PI's from a mathematical or theoretical background working with PI's from a biological background. In addition to the combined training and education which builds on both of these fields, this mechanism provides a direct way for the NSF to encourage interdisciplinary activity. It is anticipated that if the NSF requires collaboration which crosses departmental barriers, department chairs, schools, deans, and universities in general will be more likely to support such innovative research, and to remove institutional blocks to cross-department and cross-college collaborations.

We also note that as investigators devote an increasing fraction of their time and resources to biological physics and materials, some structural challenges present themselves which will require the involvement of both the funding agencies and the relevant parts of the condensed matter theory community to resolve. There needs to be an evolution in the expectations of investigators, with multi-disciplinary projects becoming the norm, rather than the traditional single-investigator grant. Moreover, Principal Investigators must be prepared to be responsive to initiatives, such as the NSF Biocomplexity effort, rather than assuming that there should be a rolling grant with long-term continuity. Another issue involves the style of research. Traditionally, condensed matter theorists have not been active in doing experimental work. However, there has been a trend for some condensed matter theorists working in biological physics to conduct their own experimental work to test, illustrate or explore their theoretical work. Others have found that the most natural way for their work to proceed is in partnership with an experimental biologist. Such efforts are not always supportable under existing NSF programs, and we recommend that the NSF introduce additional flexibility in funding modes. We also note that in some cases, funding periods of up to five years, may be warranted in view of the necessity for training physics personnel in the language and methods of biology.

Curriculum

Degree programs in biological physics can serve several important purposes. On the undergraduate level, they can be used as a mechanism for recruiting students into physics who like doing physics and mathematics, but are at the same time excited about the recent advances in biology. They can provide a home for physics courses relevant for future biologists and physicians. On the graduate level, a degree program in biological physics can help remove existing barriers between the physical and the life sciences, and emphasize the unity of science. Courses in biological physics provide a space in which exchanges of ideas between students in biology and physics take place. This is, of course, beneficial to research conducted in biological physics as its vitality and success depends on establishing a dialogue with colleagues in the life sciences.

The introduction of new degree programs will require a rethinking of the courses physics departments teach as well as degree requirements. Examples of difficult issues that we face are:- If the whole burden of teaching biological physics is borne by physics departments - what courses do we remove in order to add new courses? While such a model may work for some universities, many other universities will prefer to use courses in other departments like chemistry and biochemistry, coupled with an introductory survey course aimed primarily at physics students. This can be done at both the undergraduate and graduate level. Funding is urgently needed to retool/modernize our laboratory courses to include biological physics. There are also issues to be addressed regarding requirements for degrees. A major roadblock to biological physics training at the graduate level is the existence of rather rigid and rigorous qualifying procedures in many physics departments. These date back to when physics attracted the most talented and gifted students and was used as a “weeding out” technique. The traditional attitude is summed up by statements like “a physicist should know ….”. Such attitudes are not conducive to the development of multidisciplinary programs such as biological physics (and also materials science, astrophysics etc.). It is important to set high standards within a flexible framework. One avenue for accomplishing this is for students in biological physics to qualify for candidacy by satisfying course requirements (involving some courses outside physics and materials science departments), augmented by appropriate oral examination(s). In this way the graduate experience can be tailored to the needs of individual graduate students while maintaining high standards.

With regard to the existing courses, we recommend that more examples from biology should be used in physics undergraduate courses to illustrate points and principles, and more of the underlying physics should be included in biological courses. Such efforts also can make the point that science is more integrated than ever as one discipline and that the traditional dividing lines between areas like physics, chemistry, and biochemistry are rather arbitrary. Premedical students comprise a large population of students taking physics courses, so we should be mindful of the admissions requirements of medical schools. In particular, there is the issue of the MCAT exam and its role in determining what we teach. Finally, premed physics courses that are not calculus-based should be seriously reconsidered in light of National Academy Report BIO2010 and other calls from the life sciences community for making the biological curriculum more quantitative.

The development of new degree programs and related courses raises the issue of instructor resources. Chief among these is the need for textbooks and course syllabi for biological physics at all levels. This is gradually being met, and the internet must be utilized more to disseminate successful efforts. The NSF can facilitate this community-wide effort, perhaps by supporting a central repository for course information and sponsoring occasional workshops in this area. Thus, we encourage the NSF to support the writing of textbooks in biological physics, and to support internet resources of use to biological physics instructors.