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Demand for interdisciplinary laboratories for physiology research by undergraduate students in biosciences and biomedical engineering

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Clase KL, Hein PW, Pelaez NJ. Demand for interdisciplinary laboratories for physiology research by undergraduate students in biosciences and biomedical engineering. *Adv Physiol Educ* 32: 256–260, 2008; doi:10.1152/advan.00105.2007.—Physiology as a discipline is uniquely positioned to engage undergraduate students in interdisciplinary research in response to the 2006–2011 National Science Foundation Strategic Plan call for innovative transformational research, which emphasizes multidisciplinary projects. To prepare undergraduates for careers that cross disciplinary boundaries, students need to practice interdisciplinary communication in academic programs that connect students in diverse disciplines. This report surveys policy documents relevant to this emphasis on interdisciplinary training and suggests a changing role for physiology courses in bioscience and engineering programs. A role for a physiology course is increasingly recommended for engineering programs, but the study of physiology from an engineering perspective might differ from the study of physiology as a basic science. Indeed, physiology laboratory courses provide an arena where biomedical engineering and bioscience students can apply knowledge from both fields while cooperating in multidisciplinary teams under specified technical constraints. Because different problem-solving approaches are used by students of engineering and bioscience, instructional innovations are needed to break down stereotypes between the disciplines and create an educational environment where interdisciplinary teamwork is used to bridge differences.

laboratory education; engineering education; physiology education; design thinking

PHYSIOLOGY AS A DISCIPLINE is at a crossroads in its role in bioscience education. Recent policy reports have noted a decreased emphasis on physiology education in traditional biological science programs. However, an increased importance on physiology education is arising in the rapidly emerging biomedical engineering field. At the same time, both biosciences and biomedical engineering programs are being encouraged to engage undergraduate students in interdisciplinary research. Here, we summarize these recent changes in education policy that highlight the role of physiology for interdisciplinary science instruction. A laboratory experience is well positioned to address interdisciplinary instruction, so the unique goals of laboratory instruction for science and engineering programs is then reviewed. Differences are apparent when exploring what “discovery” means from the perspective of science versus engineering disciplines. Finally, we describe new developments at Purdue University, where an interdisciplinary physiology laboratory is being designed to break down stereotypes between the science and engineering disciplines to help students bridge the differences. In a capstone project, interdisciplinary teams of students used elements of engineering and experimental design to address a real-world problem

that was beyond the scope of a single discipline, the true purpose for the new emphasis on interdisciplinary work. Physiology is at the crossroads of the basic sciences and applied sciences, making it a suitable context for the interdisciplinary education of biomedical scientists and engineers.

Contrasting Role of Physiology in Bioscience and Engineering Programs

Concerns about the role of physiology courses in biology programs were raised when Marocco (13) reviewed 104 undergraduate biology programs from diverse public and private PhD- and non-PhD-granting institutions and found that only one-fourth of the biology programs required a physiology course. Silverthorn (19) reported, at the same time the National Research Council published *BIO2010: Transforming Undergraduate Education for Research Biologists* (8), that physiology was experiencing a decline in graduate enrollments and numbers of young faculty members. The National Research Council Committee that wrote the *BIO2010* report (8) recommended that undergraduate students in life science programs should be taught about the integration of the disciplines and how research is done and not just about specific content. According to the *BIO2010* report, “Students should be taught the way scientists think about the world, and how they analyze a scientific problem in particular” (8). Organismal physiology is mentioned in the *BIO2010* report as a possible biology

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elective for the senior level. Basic physiology concepts are listed as “Examples of Engineering Topics Suitable for Inclusion in a Biology Curriculum: the blood circulatory system and its control; fluid dynamics; pressure and force balance” (8).

Meanwhile, *The Engineer of 2020: Visions of Engineering in the New Century* (14), by the National Academy of Engineering, claimed that “Exciting breakthroughs in our understanding of human physiology have been among the most captivating topics of public discussion over the past several decades.” According to *The Engineer of 2020* (14),

As engineers seek to create products to aid physical and other activities, the strong research base in physiology, ergonomics, and human interactions with computers will expand to include cognition, the processing of information, and physiological responses to electrical, mechanical, and optical stimulation.

This conclusion is echoed by the Accreditation Board for Engineering and Technology (ABET) *2007–2008 Criteria for Accrediting Engineering Programs* (1). ABET recommends that biomedical engineering programs “demonstrate that graduates have: an understanding of biology and physiology, and the capability to apply advanced mathematics (including differential equations and statistics), science, and engineering to solve the problems at the interface of engineering and biology” (1). Within biomedical engineering programs, the role of physiology in the curriculum is becoming increasingly important. These contrasting reports with regard to the importance of physiology within curricula of bioscience and biomedical engineering programs motivated the review presented here of additional policy documents in an attempt to define a role for physiology courses in undergraduate bioscience and engineering programs.

Recommendations for Interdisciplinary Science Instruction

One way to track shifting recommendations is to examine current funding initiatives. Despite a decline in funding for instructional laboratory equipment by the National Science Foundation (NSF), funding opportunities do exist for faculty who know about the NSF investment priorities associated with goals identified in the 2006–2011 Strategic Plan. According to the current NSF Strategic Plan (16), transformational multidisciplinary research is an investment priority:

NSF will emphasize investigations that cross disciplinary boundaries and require a systems approach to address complex problems (e.g., the neural basis of behavior . . .) at the frontiers of discovery.

To reinforce this focus, the United States Congress passed, as part of the America COMPETES Act (Title VII NSF, Section 7007 Interdisciplinary Research), a bill that requires the National Science Board (NSB) to “evaluate the effectiveness of [NSF’s] efforts to engage undergraduate students in research experiences in interdisciplinary settings” (20). This law mentions the NSB, the governing board that oversees NSF operations and that also advises the President and Congress on national science policy. A 2003 NSB report (15) to the Federal Government recommended “consistent, long-term support for high-quality disciplinary and interdisciplinary doctoral training programs in Science and Engineering.”

The mention of student research experiences in interdisciplinary settings also aligns with the National Academy of

Engineering’s *Educating the Engineer of 2020: Adapting Engineering Education to the New Century* recommendation that interdisciplinary learning should start at the undergraduate level rather than waiting until graduate degree programs (3). The *Educating the Engineer of 2020* report was written by a committee of the National Academy of Engineering, one of four organizations that comprise the National Academies, along with the National Academy of Sciences, the Institute of Medicine, and the National Research Council. The National Academies Committee on Science, Engineering, and Public Policy defines interdisciplinary research as follows (4):

A mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialized knowledge to advance fundamental understanding to solve problems whose solutions are beyond the scope of a single discipline or area of research practice.

According to *The Engineer of 2020: Visions of Engineering in the New Century* (14), because real-world problems rarely fit within a single discipline, the preparation of scientists and engineers needs to be better aligned with the interdisciplinary skills for which there will be an increasing demand.

Also consistent with the NSB’s emphasis on interdisciplinary research are changes recommended for biomedical science training. In a conference convened to assess the role of private funding to ensure adequate training of biomedical scientists, the first conclusion was the following:

In the postgenomic era of research, multidisciplinary and interdisciplinary research will command center stage, requiring team approaches and the collaboration of many individuals from vastly different fields, ranging from computational mathematics to clinical science (2).

Furthermore, a report (6) from the National Research Council, *Addressing the Nation’s Changing Needs for Biomedical and Behavioral Scientists*, stated that “The [National Institutes of Health] should expand its emphasis on multidisciplinary training in the basic biomedical sciences” as one of five recommendations. This recommendation was repeated as one of eight recommended changes according to the *BIO2010* report (8), which states that “Laboratory courses should be as interdisciplinary as possible, since laboratory experiments that confront students with real-world observations do not separate well into conventional disciplines.” Both engineering and bioscience recommendations agree that the future of biomedical research requires training in interdisciplinary interactions.

Since the problems of the future are expected to extend beyond the boundaries of any single discipline, the integration of physiology with other disciplines can be explored as a way to educate students to innovate and find solutions. Educators are being asked to provide interdisciplinary experiences and research activities relevant to society in courses that involve data gathering and analysis (4). Furthermore, in a time of declining enrollments in science and engineering disciplines, it is quite possible that students will be more attracted to interdisciplinary courses where they deal with problems of social importance, such as the application of engineering tools and problem-solving approaches to physiology problems. As posed by the documents reviewed here, the interdisciplinary programs of the future will involve hands-on research experience

and so are more appropriate to a laboratory than to lecture-based courses.

Goals for Laboratory-Based Instruction

The idea to examine how an interdisciplinary laboratory course might help students meet objectives identified for science and engineering programs was motivated by a new cross-listed physiology laboratory course for both biology and biomedical engineering students at Purdue University. A course that provides experiences for interdisciplinary teams of students to solve problems that are beyond the scope of a single discipline will need to address the expected outcomes from each disciplinary perspective. Laboratory goals for science were identified in a 2006 report (5) by the Committee on High School Labs: Role and Vision of the National Research Council. The committee was asked to identify what can be accomplished with an instructional laboratory that cannot be accomplished without such a laboratory experience (5). The report identified seven basic laboratory outcomes for high school laboratories. It is interesting to consider to what degree these outcomes are also expected for undergraduate engineering and science laboratory experiences. According to their exhaustive review of the literature, the Committee on High School Labs found that a typical instructional laboratory activity helps students meet some of these goals:

1. Learning the subject matter.
2. Developing practical skills such as the collection and analysis of data.
3. Developing scientific reasoning including experimental design.
4. Developing teamwork abilities.
5. Understanding the nature of science.
6. Becoming interested in science and in learning science.
7. Understanding the complexity and ambiguity of empirical work.

Some of the basic laboratory outcomes mentioned in *America's Lab Report* (5) are reinforced by other reports on outcomes from science research experience at the undergraduate level. A large survey study (18) reported about the effects on students from undergraduate research experiences and factors that relate to positive outcomes. It was found that undergraduate students with research experiences had high grade point averages, and many research students changed their career plans and decided to pursue a doctorate in science or engineering (17). Several reports have confirmed that undergraduate research experiences provide science students with science knowledge, practical skills, understanding of the nature of science, teamwork abilities, and interest in science and in learning science. Studies (9, 21) have shown that undergraduate students actively engaged in research have a better understanding of how scientific knowledge is built, improve their understanding of scientific principles, and assimilate new knowledge more effectively with active, inquiry-based collaborative learning and creative thinking. Another report (11) based on a study of students in four liberal arts colleges found that participating students who chose to do research at the undergraduate level and their faculty advisors independently concurred that the strongest effects of a research experience were on aspects of personal-professional growth. More specifically, outcomes included confidence to contribute to science and to work collegially; application of scientific knowledge to

research problems; development of attitudes, behaviors, and skills essential to good research; increased interest in and identification with science as a profession; and readiness to undertake graduate work.

At Purdue University, College of Science faculty members recently voted to implement new requirements for graduation. Undergraduate students are now expected to demonstrate their ability to communicate effectively as scientists in both an oral form and a written form. Science students must develop technical presentations with a clear purpose suited to the audience and with technical information organized logically, clearly, and concisely. In addition, students must make strong, persuasive arguments, employ appropriate visual aids, and answer questions. Research in an undergraduate laboratory course provides students with the opportunity to practice these skills. As another undergraduate requirement, Purdue science students must demonstrate the ability to collaborate as part of a team, including knowing the function and purpose of the team and the roles of team members who work toward a common goal. As part of effective team collaboration, science students are expected to use effective communication, recognize and use the strengths of each member, and demonstrate skills to manage and resolve conflicts. A laboratory course may be best suited to help students meet these goals, accepted by Purdue University College of Science faculty members as undergraduate graduation requirements starting in 2007.

Yet in developing interdisciplinary laboratory experiences, it is also important to consider the desired outcomes for an engineering laboratory experience. Indeed, it is important to examine the different goals of an engineering laboratory as opposed to those of a biological sciences laboratory. The following goals were identified by Feisel and Rosa (10) for engineering laboratory experiences. Students should be able to

1. Apply appropriate instrumentation, including software tools to make measurements.
2. Identify strengths and limitations of theoretical models.
3. Devise an experimental approach, specifying and implementing equipment and procedures to take and interpret data to characterize engineering materials, components, or systems.
4. Analyze and interpret data.
5. Select, modify, and operate appropriate engineering tools.
6. Design, build, or assemble a part, product, or system.
7. Identify and learn from unsuccessful outcomes.
8. Demonstrate levels of independent thought, creativity, and capability in solving real-world problems.
9. Understand the impact of engineering solutions in global and societal contexts.

These goals for engineering laboratory experiences are similar to those for science laboratory courses, but there are notable differences.

To illustrate the similarities and differences, consider how a biologist and an engineer might approach a problem related to lung function. The biologist might ask questions about the mechanism that causes altered lung function. Multiple hypotheses might be posed, and an experimental test of a hypothesis would help the scientist rule out some of the explanations to approach an understanding of the actual mechanism. In the process, the scientist would be using *goals 1–5* for engineering laboratory experiences (instrumentation for measures, theoretical models, an experimental approach, data analysis, and selection of appropriate tools). In contrast, an engineer might

ask what they could do for people with a lung function problem to help them breathe. The engineer would focus on the problem and attempt to design a solution (*goal 6*), and then the design would be tested (*goal 7*). The science is the same, but the engineering question calls for action with an immediate impact on people (*goal 9*) and with several different potential answers to the problem (*goal 8*). The engineering goals provide an alternative view on the purposes of an instructional laboratory course that may also be applicable to the professional goals some science students have for their physiology laboratory courses.

Another significant difference between biologists and engineers relates to the complexity of systems. When engineers speak of a system (*goal 6*), they mean “components that work together to provide a desired function” (7). Learning to design functional systems is a focus for engineers in a laboratory course, where they “design under constraints” (7) to meet desired needs within limits set by economic, environmental, social, political, ethical, health, or safety considerations (*goal 9*). An engineer uses a simplified model when designing a system, in contrast to the biologist, who may view a living system with all of its complexity and identify patterns without wanting to oversimplify the complexity. Yet, increasingly, biomedical engineering programs are appreciating the need to expose their students to the complexity and variation of living organisms. This is apparent through the increasing interest in providing physiology laboratory experiences appropriate to this student population. According to ABET’s 2007–2008 *Criteria for Accrediting Engineering Programs* (1), biomedical engineering students should be able to “make measurements on and interpret data from living systems, addressing the problems associated with the interaction between living and non-living materials and systems.” ABET criteria are used by engineering institutions to design both a process for ongoing review of the objectives and a process to measure the graduates’ achievements of these objectives. Clearly, the biomedical engineering graduates who have had hands-on physiology laboratory experiences as part of their studies will have addressed “the problems associated with the interaction between living and non-living material” as required by the accreditation criteria (1).

Interdisciplinary Physiology Laboratory Activities

Interdisciplinary physiology laboratory activities were developed by a multidisciplinary team of faculty members from Basic Medical Sciences, the Weldon School of Biomedical Engineering, and the Department of Biological Sciences at Purdue University. The laboratory activities were developed for a new team-based course, “Measurement and Design in Physiology Systems,” where both engineering and science disciplinary perspectives were presented to mixed discipline teams of students. Teams of biology and biomedical engineering students populated the pilot course to experiment, design systems, and solve problems related to physiology. As far as we know, a multidisciplinary undergraduate physiology laboratory course did not previously exist. The physiology laboratory provided an environment where the similar as well as unique disciplinary desired outcomes were reached through slight modifications of physiology activities to create interdisciplinary physiology laboratory experiences.

In developing the interdisciplinary physiology laboratory course at Purdue University, the importance of communication

was established early, a desired outcome in any discipline. One means by which communication was emphasized was by having the students from the different disciplines educate their counterparts on an area in the laboratory relevant to their discipline. For example, a spirometry module was initiated with the biology students teaching their engineering peers about the elements of the respiratory system and the mechanisms for air flow and gas exchange. In return, the engineering students described the mechanical elements and principles that govern spirometry using a pneumotachometer. This education process was paramount in establishing equal footing between students of the different disciplines. Elements of the module that were engineering in nature were separated from those that were inherently biological to establish value for both disciplines.

Both experimental and engineering design processes were identified as key components in the interdisciplinary laboratory course. An understanding of both of these processes was emphasized throughout the course. Again, in the spirometry module, the teams were charged with an engineering design project to build a Fleisch pneumotach head for measuring normal tidal breathing. The exercise was directed in that the element to be varied was the resistive component of the pneumotachometer head. The engineering students had a background in engineering design, so they took the lead in this section of the module. Yet, a subsequent section of the module required experimental design, where the biology students directed the identification of hypotheses to be tested and the variables to be modified. The students identified a question to address (such as how breathing rates vary at rest versus with mild exercise) and then designed an experiment and a method for analysis to reveal patterns in responses despite the variation found among the experimental subjects. This equal emphasis on the engineering and experimental design processes not only addressed desired discipline specific objectives but also enlightened the students to alternative ways of thinking.

A final capstone project for this course incorporated both science and engineering goals. Students were posed with the task of designing a device to measure pulmonary edema. This was initiated as a classic engineering design project where criteria were established, multiple devices were proposed, and designs were critiqued to assess how well the proposed devices met the design criteria. As part of this design process, the teams also needed to develop models of pulmonary edema to test their proposed devices. These models were experimentally validated. The project required expertise in the basic biology and pathophysiology involved in pulmonary edema as well as an understanding of instrumentation and how physical measurements can be made. Students presented their projects at the end of the semester in a final demonstration of how working as an interdisciplinary team allowed the group to address a real problem that was beyond the scope of a single discipline.

Discussion and Summary

Recent collaboration of biological scientists with engineers has produced equipment to extend the frontiers of both basic and applied research. For example, advances in mass spectrometry and DNA sequencing instrumentation significantly contributed to the emerging research areas of genomics and proteomics, where scientists and engineers continue to collaborate. Physiomic research represents another developing field where

engineers and scientists are working together to investigate models of physiological processes. It is likely that teams of engineers and basic scientists working together will continue to advance emerging frontiers in biomedical research. Solutions to many societal problems will lie at the interface between the disciplines, and it will be up to current faculty to provide interdisciplinary instructional experiences where the different problem-solving approaches unique to disciplines are recognized and appreciated. Physiology is uniquely poised at the interface of biology and engineering as a common field for both disciplines to foster the skills necessary to function as part of a multidisciplinary team.

This report is intended to help faculty define and assess the benefits undergraduate students would receive from carefully designed interdisciplinary physiology laboratory instruction. The NSF Strategic Plan (16) provides new emphasis on partnerships among community and technical colleges, 4-yr colleges, and research-intensive universities in the United States. Collaboration with physiology educators in other countries is another way to find out how others deal with the issues described here. Finally, because NSF funding is driven, in part, by proposal pressure, it is our hope that this review of interdisciplinary laboratory objectives will inspire faculty members to consider how their physiology course is related to another discipline's approach so that grant proposals can be written to develop new collaborations to benefit the next generation of students. Innovations that further these goals will benefit science, the workforce, future innovation, and the quality of physiology instruction.

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