A new paradigm for graduate research and training in the biomedical sciences and engineering

J. D. Humphrey, G. L. Coté, J. R. Walton, G. A. Meininger, and G. A. Laine. A new paradigm for graduate research and training in the biomedical sciences and engineering. Adv Physiol Educ 29: 98–102, 2005; doi:10.1152/advan.00053.2004.—98Emphasis on the individual investigator has fostered discovery for centuries, yet it is now recognized that the complexity of problems in the biomedical sciences and engineering requires collaborative efforts from individuals having diverse training and expertise. Various approaches can facilitate interdisciplinary interactions, but we submit that there is a critical need for a new educational paradigm for the way that we train biomedical engineers, life scientists, and mathematicians. We cannot continue to train graduate students in isolation within single disciplines, nor can we ask any one individual to learn all the essentials of biology, engineering, and mathematics. We must transform how students are trained and incorporate how real-world research and development are done—in diverse, interdisciplinary teams. Our fundamental vision is to create an innovative paradigm for graduate research and training that yields a new generation of biomedical engineers, life scientists, and mathematicians that is more diverse and that embraces and actively pursues a truly interdisciplinary, team-based approach to research based on a known benefit and mutual respect. In this paper, we describe our attempt to accomplish this via focused training in biomechanics, biomedical optics, mathematics, mechano-biology, and physiology. The overall approach is applicable, however, to most areas of biomedical research.

HISTORY OF SCIENCE, mathematics, medicine, and engineering reveals that great advances have often been made by the individual (e.g., 1, 5, 14). From antiquity to the Renaissance, we recall the tremendous individual accomplishments by Aristotle (384–322 BC), Archimedes (287–212, BC), or Galen (129–199 AD) to those of Leonardo (1452–1519), Galileo (1564–1642), or Harvey (1578–1657). Not only did the findings of these great men give directions to subsequent investigation, their very example of inquiry served as a paradigm for the way students were trained, largely as apprentices to the masters. Notwithstanding the tremendous changes brought forth by the birth of both modern science and the modern university, advances continued to come primarily from individuals. We quickly think of, for example, Hooke (1635–1703), Newton (1642–1727), Euler (1707–1783), Gauss (1777–1855), Pasteur (1822–1895), Maxwell (1831–1879), and Einstein (1879–1955). Indeed, the imagery of Newton, driven by the great plague of 1664–1665 from Cambridge University to his native Woolsthorpe, and working in isolation to invent the calculus, to discover the universal law of gravitation, and to prove that white light consists of a spectrum of colors (20), reinforces the concept of the individual investigator. This is consistent with the commentary by Descartes (1596–1650) that “Truths are more likely to have been discovered by one man than by a nation” (4).

In addition to recognizing the central position of these and other individual investigators in advancing knowledge, it is interesting to consider the means by which they communicated their findings. We quickly think of the impact of Euclid’s Elements, Aristotle’s Physics, Galileo’s Dialogues, Harvey’s On the Motion of the Heart and Blood, or Newton’s Principia, to name a few. Again, the single-author book subtly conveyed the importance of the individual and his/her ability to elaborate great ideas. It is somewhat surprising, therefore, that this individualistic trend continued into the 20th century, despite how the technical paper emerged in the mid-17th century. According to Boorstin, “While works of science were often large tomes easy to stop for censorship, the novel observations in a letter could slip in unnoticed or be delivered with the ‘ordinary post’.” (4). Hence, the letter, which later gave rise to the scientific paper, became the preferred means by which the great scientists communicated “...a fact or a small cluster of facts...” with colleagues. Although it would seem that the increased ability to exchange ideas, and thus critique or nurture early findings, would have led to significant collaboration and joint authorship, this was not the case. Individual investigators continued to expound individual ideas regardless of the published format.

Beginning in the mid-20th century, however, a complementary research paradigm arose. Particularly significant advances in science, engineering, and medicine came not just from the individual investigator, but also from large groups of researchers brought together to solve a specific problem. Prime examples include the Manhattan Project, where nuclear energy was harnessed and displayed that fateful day in 1945, the Apollo Project, which culminated in perhaps man’s greatest technical achievement to date, landing on the moon in 1969, and the Human Genome Project, which culminated in 2000 and ushered in the “omic” era (9–11). There were, for example, ~150,000 people working on the Manhattan Project, few of whom knew the overall goal of the project, but all of whom contributed to its eventual success. Therein was born the concept of team science, albeit on an enormous scale. Of
course, not all teams need to be huge to be effective. Indeed, the majority of the effective teams in biomedical research continue to consist of <10 members, often only three to seven members. This is reflected, in part, in the average number of authors per paper, which has continued to increase significantly over the past decades (8, 18). The essential question to educators, therefore, is, How can we facilitate this desirable and natural tendency toward interdisciplinary research?

Recently, there has been increasing attention by universities and funding agencies to actively encourage and promote the concept of team science. At Texas A&M University, for example, the Office of the Vice President of Research has provided seed funds to promote Interdisciplinary Research Initiatives and Life Science Initiatives that bring together investigators from multiple disciplines to work on a common project. Indeed, many universities have constructed buildings that house investigators according to common interests, not departmental or disciplinary affiliations. So, too, have funding agencies such as The National Institutes of Health (NIH) begun to promote team science through programs such as the Bioengineering Research Partnerships. Indeed, the Bioengineering Consortium (BECON) at NIH recently sponsored a symposium entitled Catalyzing Team Science (15a). One of the main conclusions was that “Effective teams begin with compelling conclusions was that “Effective teams begin with compelling reasonsthat bring the team together and encourages collaboration. and that not only include the different knowledge bases and languages of biology, engineering, and mathematics, but also basic philosophical differences (7, 15). Whereas life sciences tend toward an inductive (Baconian) approach, engineering and mathematics tend toward a deductive (Cartesian) approach. Whereas life science tends toward reductionism, engineering and mathematics often seek generality. These differences must be addressed directly and discussed openly to become complementary rather than to remain as barriers.

Three primary ways to reveal what diverse individuals from different disciplines offer are 1) to highlight successful case studies of cooperation, 2) to increase mutual interactions, and 3) to facilitate interdisciplinary approaches via consistent opportunities to solve problems as a team. It is our experience that simply forming interdisciplinary faculties and team-teaching interdisciplinary courses does not go far enough in impacting student attitudes or capabilities. Our goal, in contrast, is to bring PhD students in biomedical engineering, life sciences, and mathematics into the same classrooms, seminars, local symposia, workshops, and research laboratories where they can learn firsthand the benefits of an interdisciplinary team-based approach. They do this, in part, through active practice in problem-based learning (PBL) courses (cf. Refs. 12, 16) and via collaborative research dissertations that are codirected by investigators from different disciplines to ensure that the interdisciplinary approach is integrated throughout the student’s entire educational experience.

**Formal coursework.** Our experiment impacts four different PhD programs in four departments (Biomedical Engineering, Mathematics, Medical Physiology, and Veterinary Physiology and Pharmacology) within four colleges (Colleges of Engineering, Science, Medicine, and Veterinary Medicine). It is centered on coordinated changes in curricula that seek to change the attitudes and perspectives of the students so that they learn to embrace and actively pursue interdisciplinary collaborations based on a known benefit and mutual respect. To encourage attitudinal changes in life scientists, we have proposed a course entitled Modeling in Vascular Biology (3 credits). This course is not designed to be mathematically intensive; rather, it seeks to emphasize the motivations, methods, and successes of modeling and design in vascular biology and clinical care. For example, students will explore why Linus Pauling, 1954 Nobel Laureate and discoverer of the α-helix motif, “…attributed the birth and development of molecular biology to the theoretical approach of physics…” (13). Indeed, Pauling writes, “I remembered a theorem that had turned up in a course in mathematics that I had attended, with Professor Harry Bateman as

**A NEW PARADIGM**

Various approaches can facilitate interdisciplinary interactions, but we submit that there is a critical need for a new educational paradigm for team-based, interdisciplinary graduate research and training that we conceived in 2002 and have begun to implement at Texas A&M University and the Texas A&M University System Health Science Center. What we describe is an experiment in progress, not a conclusion. We hope, therefore, that this paper stimulates others to design competing experiments to hasten the refinement of improved paradigms for preparing diverse students for careers in team science. Although our focus is on vascular research, the proposed paradigm can be implemented for any central problem in biomedical science and engineering.
the teacher, in Pasadena twenty-five years before. This theorem states that the most general operation that converts an asymmetric object into an equivalent asymmetric object (such as an L amino acid into another molecule of the same L amino acid) is a rotation-translation—that is, a rotation around an axis combined with a translation along the axis—and that repetition of this operation produces a helix.” (13). Life science students must learn to seek collaborations with engineers and mathematicians as they too seek to discover the secrets of nature.

To effect a similar attitudinal change in engineers and mathematicians, we propose a course entitled Methods in Vascular Biology (3 credits). This course seeks to reveal key findings in molecular and cell biology, to motivate the hypothesis-driven nature of many biomedical studies and, perhaps most importantly, to review the arsenal of tools available to the biologist (e.g., the atomic force microscope, laser tweezers, multiphoton microscopy, RT-PCR, DNA microarrays) to probe the underlying mechanisms of mechanotransduction. In other words, we submit that bioengineers and mathematicians need not be trained as biologists, but they must know what data can be collected and what tools can be used. Without such knowledge, they cannot participate in the creative part of experimental design nor can they develop new theories based on that which is possible rather than that which is known. In summary, engineers, life scientists, and mathematicians must know what expertise (e.g., tools) the others offer or else there will be no motivation to seek collaboration in specific circumstances.

One course alone (per group) does not ensure desired, sustained changes. All students must improve their ability to communicate across disciplines and to appreciate fully the need for collaboration. Thus we propose three new courses to bring diverse students together into the same classrooms. Communication and Ethics (2 credits) focuses on writing well, including how to write and publish a scientific paper and how to write a research proposal, presenting well orally, and promoting scientific integrity. Perhaps most importantly, however, it addresses communication across disciplines; it has been said that we each have but one story to tell, we simply tell it in different ways to different people. Students must be trained to present the same research findings in different ways to different audiences, ranging from mathematicians to physicians to venture capitalists. This course, developed in consultation with the Departments of English and Communication at Texas A&M, also emphasizes team skills. For example, student teams consisting of a life scientist, engineer, and mathematician work together to write a short review article and submit it formally (including an appropriate cover letter) to the faculty coordinator who serves as a “journal editor.” The papers are then sent out for review by student teams and undergo one round of revision. This section ends with a discussion of galley proofs, proofreader marks, and issues of copyright so that the students appreciate the full scope of getting published.

Case Studies (1 credit) presents a particular clinical need, then discusses early clinical solutions, different philosophies of approach, the scientific method, experimental design, prototype development, animal research and clinical trials, FDA regulatory issues, and patenting and technology transfer. This course is taught via a series of coordinated lectures by appropriate experts, including local physicians, industrial representatives, and officials from the University Laboratory Animal Care Committee, the Institutional Review Board, which ensures compliance in research on humans, and the Office of Technology Licensing. The key is that students appreciate the full breadth of challenges in modern medicine and how research and development are actually done, i.e., solutions demand important contributions from diverse individuals within an environment of mutual respect and one that respects compliance issues. Both of these courses have been piloted and have received strong reviews from the students.

Finally, we propose a capstone PBL course called Problems in Vascular Mechanobiology (3 credits), where teams of students attack a real-life problem, similar to a case study, which requires the integration of concepts from multiple disciplines (in our curriculum, these are biology, biomechanics, biomedical optics, mathematical modeling, and physiology). Sections are to be co-taught by a life scientist and a biomedical engineer/mathematician. In an ideal scenario, each section consists of 12 PhD students (3 biooptical engineers, 3 biomechanical engineers, 3 life scientists, and 3 mathematicians). Teams are first assigned by discipline and given the same problem; a proposal outlining a potential approach is required at the end of 3 wk. Thereafter, the students are redivided into interdisciplinary teams, each consisting of a biooptical engineer, a biomechanical engineer, a life scientist, and a mathematician. The new teams spend the remainder of the semester investigating an interdisciplinary-based solution; this will result in a research proposal and a condensed version for use as an instructional module in an undergraduate course. At the end of the semester, the teams orally present their final ideas and review each other’s proposals (again reinforcing skills learned in the communications course). The proposals are discussed/evaluated in two ways: first, for scientific plausibility and second, as indicators of attitudinal changes. The latter is possible by comparing approaches taken by the disciplinary vs. interdisciplinary teams, which are also assessed via summative and formative evaluations by an external professional. It is essential to note early on in this PBL experience that all teams need a leader, but leadership means responsibility to the team not superiority over the team. Indeed, it is essential to train students to learn when they should assume a leadership role and when they should not. In other words, they must learn to expect a leadership role in select projects while being equally comfortable not leading other projects. If the primary goal of the project is to develop instrumentation, the engineer should take the lead; if the primary goal is to develop an animal model, the biologist should take the lead. Again, the concept of building teams based on mutual respect and a known benefit should permeate the learning experience.

Whereas one cross-cultural course and three common courses (Fig. 1) will help evoke attitudinal changes in all students, each person must also have unique strengths to contribute effectively to a team. Hence, in addition to departmental electives, we require separate 12-credit cores in each of the four areas. These can be designed according to the strengths of each department. The resulting 24-credit coordinated curricula (Fig. 1) for each group will help achieve our goal of broadly preparing students for leadership positions in interdisciplinary research and development in industry or academia.

It is noted that these coordinated curricula address How People Learn (3, 6). That is, the courses Modeling in Biology...
and Methods in Biology allow the instructor(s) to uncover and address different, discipline-based preconceptions that the students bring to their research. Identifying such preconceptions and learning those of others is the first step toward appreciating the mutual benefits of team science. The core courses allow students to develop specific depth, whereas the Case Studies course allows this factual knowledge to be organized within a new conceptual framework, one that emphasizes the different, essential, complementary roles of the different professions. The PBL course allows the students to monitor how they learn to solve problems, particularly compared with others who have different philosophical approaches for formulating and solving problems, and eventually how they can become an effective member of a diverse team. Finally, recall from above that three problems, and eventually how they can become an effective member of a diverse team. These courses encourage diverse students to embrace and actively pursue team-based research, yet a focused, collaborative dissertation experience, with required coadvisors from different disciplines, ensures the success of this new educational paradigm (Fig. 1). The student’s dissertation committee ensures that the core courses truly provide the necessary technical foundations for rich, innovative dissertations, and an interdisciplinary Program Steering Committee ensures that all dissertations embrace close interactions between multiple students/faculty from allied disciplines.

**DISCUSSION**

At this juncture, it is appropriate to consider the evolution of the philosophy of training students. Toward this end, consider the following provocative assessment by Van Doran (19). “The Aristotelean ideal of the educated person, ‘critical’ in all or almost all branches of knowledge, survived for centuries as the aim of a liberal education. . . . The twentieth century has seen radical change in this traditional scheme of education. The failure of the Renaissance to produce successful ‘Renaissance men’ did not go unnoticed. . . . The alternative became self-evident: achieve expertise in one field while others attained expertise in theirs. . . . The convenient device for accomplishing the change consisted of a divided and subdivided university, as the knowledge base continues to grow rapidly, perhaps exponentially, these subsets continue to subdivide and shrink. We no longer have situations where individuals choose between biology and engineering or even between botany and zoology and mechanical vs. chemical vs. electrical engineering. Rather, we now have endothelial biologists who focus on one cell type within one physiological system, and we have bioengineers who may focus on one approach to address one particular disease (e.g., the solid mechanics associated with stent design). Indeed, even in mathematics, where one often expects greater generality, the move has long been toward specialization. Bell (1) suggested, for example, that Henri Poincaré (1854–1912) “. . . was the last man to take practically all mathematics, both pure and applied, as his province. It is generally believed that it would be impossible for any human being starting today (circa 1937) to understand comprehensively, much less to do creative work of high quality in more than two of the four main divisions of mathematics—arithmetic,
algebra, geometry, analysis, to say nothing of astronomy and mathematical physics.”

The need to move toward true team-based research, particularly in medicine, is now well recognized. Dr. Harold Varmus, then Director of the NIH, said it this way: “... biological problems are too complex to be solved by biologists alone; we need partners in many disciplines. . .” (15b). More recently, the NIH BECON 2003 Symposium–Catalyzing Team Science summarized it as: “The complexity of modern science and technology increasingly requires true collaborative efforts from individuals with different training and expertise to realize the benefits of these advances for health and medical care.” Regardless of how it is stated, the need for team-based research implies the need for new ideas and instructional methods for training the next generation of investigators.

Clearly, there is no single paradigm for success, nor should there be. Fostering diverse paradigms will help meet the increasingly diverse needs of academia, government, and industry to address the most pressing challenges of the day and to continue the rapid growth of knowledge. Nevertheless, we submit that one logical possibility is to begin to train PhD students in the way that research and development is most often done—in interdisciplinary teams. Such training must be based on a sense of mutual benefit, it must involve attitudinal changes, it must increase interactions among the disciplines, and it must be highly coordinated. Herein, we have presented one possible paradigm, one that is based on coordinated changes in curriculum in four departments across four colleges at Texas A&M University, one that integrates interactions among students and faculty from different departments, and one that culminates in a truly interdisciplinary dissertation that requires consistent direct interactions among students and faculty from multiple departments. We certainly expect our program to evolve, but we hope that reporting the current programmatic structure will stimulate others to develop and assess similar team-based approaches to graduate training and research.

GRANTS

This work was supported, in part, by two Special Opportunity Awards from The Whitaker Foundation as well as generous support to Texas A&M University by Carolyn S. and Tommie E. Lohman. We also acknowledge our Cardiovascular Research Institute and M. E. DeBakey Institute, both of which seek to promote interdisciplinary research.

REFERENCES