Building the Renaissance Team

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Recent research using tools from the biological, mathematical and computer sciences has led to dramatic improvement in our understanding of biology, medicine, and the environment. New fields such as bioinformatics and data mining combined with powerful new computational tools are answering important biological questions. They are also generating new questions, thus defining the frontier of research in the life sciences. As these new cross-disciplinary fields continue to develop new knowledge, techniques, and processes, they create even more opportunities for new biological research.

To cite one example among many, biologists were able to work out the structure of proteins by using a mixture of rigorous strategies (e.g., dynamic programming) and heuristic methods to align sequences. This led to the discovery of domains in proteins—discrete portions of a protein with their own function. Subsequently, biologists discovered that protein sequences are conserved over vast evolutionary distances (e.g., Thornton and DeSalle, 2000). One result has been a growth industry in developing and using methods to align sequences.

If the potential of these exciting new avenues of research is to be realized, a new generation of scientists will be needed. Clearly if biologists, mathematicians, and computer scientists are to work together to solve complex biological questions, more diverse training will be needed at all stages of education. Of course, it is impossible to know in advance which students will choose careers in fields such as biology, biotechnology, or medicine. Thus we need to view all undergraduate biology, computer science, and mathematics majors as potential researchers in biology and the medical sciences. To accomplish this, educational programs need to be redesigned to prepare students to work in the kinds of cross-disciplinary teams required by the "new biology" (Brewer and Gross, 2003).

Although it is impossible to forecast the future, we can safely predict that most students will change careers several times during their lives and that those who do stay in the same career will often find that the nature of their work has changed. So the issue for educators (and their students) becomes: "What skills will the next generation of life scientists need? What can educators do now to ensure that their graduates have the skills they need for future careers in the life sciences?" In this short paper, we will look at what skills students might need in the future, what an ideal working team might look like, and what barriers need to be addressed to achieve these goals. At the end we offer one example of an integrated curriculum designed to develop the skills we believe students need.

Scientists, mathematicians, and educators poised at the beginning of a new century of discovery in the biological sciences need to fully investigate these new questions and not be satisfied with old answers. How we mobilize today to meet the challenges of the future will determine how well prepared our graduates will be to explore and participate in these new intellectual frontiers.

What Students Need

Regardless of their interests, pre-college preparation, declared majors, or career goals, if undergraduates are to be competitive in an ever-changing work environment they must be prepared to adapt and learn new material quickly. Students must learn how to think critically, to evaluate evidence, and to solve open-ended problems. Ideally, they should also have experience working in teams on problems that are inherently interdisciplinary. To this end, all students should have opportunities to take courses that blend theory and practice and provide research-like activities and projects. In addition, courses should focus on process supported by cogent content examples and plenty of open-ended problems.

These general goals are particularly relevant to undergraduate biology, mathematics, or computer science curricula. Even though many students in these subjects do not end up working in their major field (however broadly we define it), much less in biological or medical research, colleges still must prepare all students to be critical thinkers and scientifically literate citizens. Moreover, regardless of where their career paths might eventually lead them, at some point in their careers most graduates will work on a cross-disciplinary team. Therefore, we need to prepare all majors to work together and to view their disciplines as interconnected. In the words of the National Research Council's report *Bio 2010* (NRC, 2003), it is necessary that "interdisciplinary thinking and work become second nature."

In the past, those who pursued careers in biology or medicine rarely studied mathematics or computer science in depth; in fact, many were mathematics- and technology-averse. Today, however, it is nearly impossible for a student to pursue a career in life science research without having a strong foundation in both of these fields. In addition, whether investigators are focusing on evolutionary biology, genomics, or environmental change, it is unlikely that a single individual will know everything necessary to pursue these new avenues of research alone. More likely, research will be conducted by multi-disciplinary teams to which biologists, mathematicians, and computer scientists all contribute. This is true equally in both basic research (e.g., decoding the DNA of a virus) and applied investigations (e.g., monitoring the spread of SARS). For example, creating a flu vaccine each year requires analysis of data from prior years, probabilistic estimates of various paths in the evolution of the virus, the economics of manufacturing and distribution, and the politics of possible misjudgments in the seriousness of thc threat—a truly interdisciplinary exercise.

Regardless of the disciplines represented, interdisciplinary teams work best if everyone has some knowledge of the big picture and some understanding of what each member of the team is contributing. Thus, whether or not they find themselves in a research environment, those working in biology or biotechnology need to understand and be able to use mathematics and computer science. For the same reasons, mathematicians and computer science need to know enough biology to understand the key questions so that they can help develop the tools required to solve these problems. College faculty need to examine seriously whether undergraduates, regardless of their career paths, are being prepared to participate in a multidisciplinary world where teamwork and sharing expertise is becoming less the exception and more the rule.

Seeking New Foundations

Educators' traditional response to what students need to know is to simply list the courses they should take during their undergraduate studies and the general topics which they should be exposed to. But what does "exposed to" mean when setting up an actual curriculum with real courses and syllabi? Does it mean providing superficial coverage or in-depth opportunities to explore the topics? Does it mean being prepared for the next course in the sequence or for more work in thc field, while also encouraging the student to want to work in the field?

For example, biology students of the future will need a strong foundation in probability theory and stochastic processes. Ecology, genetics, and medical testing cannot be understood without understanding statistics and probability theory. The same is true for epidemiology, which started with deterministic models but has since moved on to using more stochastic modeling. Mathematics and computer science students, on the other hand, will need a good foundation in biological principles along with a basic understanding of some of the questions at the frontier of modern biology in areas such as genomics, evolutionary biology, and biocomplexity.

Within the current curriculum the only way students can prepare for the cross-disciplinary needs of diverse careers in the biological and health sciences is to major in one area of science or mathematics and take as many classes as possible in another area. Computer and mathematics students might take classes in the basics of biology, chemistry, and physics, while biology students, might include classes in calculus, probability theory, linear algebra, and databases. But for almost all students this option is too inefficient and expensive since it extends an already full program beyond what can reasonably by accomplished in a standard four year undergraduate program.

Instead, we propose an alternative approach that places students at the center of the educational enterprise and defines education by means of outcomes rather than time or credits. Rather than ask what classes should students take, we work backwards from what we would like our students to be able to do.

The Ideal Cross-Disciplinary Team

When approaching any interdisciplinary question, members of a research team are not necessarily experts in all relevant areas. In fact, rarely are team members strong in all areas of concern. Rather, they bring to the question areas of strength and an ability to communicate and collaborate with others with complementary training and interests. To help define what this means for students, we've identified four areas required for members for our renaissance team: content expertise, shared knowledge, communication skills, and teamwork.

Content Expertise. To be a contributing member of a team, all members need at minimum in-depth applied expertise in one critical area of the investigation, be it ecological diversity, population biology, modeling environmental change, or visualizing large sets of data over time (e.g., population densities). Such expertise would include having participated as a student in research projects in the area of study. Abstract knowledge of modeling techniques and traditional models is not enough. Instead, students need experience working in a real world setting, collecting and examining data, attempting to fit models to those data, and trying to learn from the models.

Shared Knowledge. As noted above, no single member of a team can be expected to have expertise in all relevant areas. It is expected, however, that all members of the team have a strong foundation in the general areas under investigation. In fields where they are not experts, team members should be able to ask good questions and read in other disciplines in order to better understand the problems in that field.

While a mathematician or computer scientist might not know specific details about a specific biological situation (for example, biological diversity of salmon), she or he should understand the basic principles of population biology and genetic diversity, and the critical role rivers play in fish spawning. On the other hand, a fish biologist working on salmon recovery might not know how to model population diversity including influences such as weather, genetic variability, or the potential breaching of dams, but he or she should know that these are critical factors for constructing robust models. The biologist needs to be able to critique proposed models for predicting how changes in one factor might affect salmon recovery, including the assumptions upon which the models are based. Computer scientists, on the other hand, must understand the models well enough to be able to extract biologically useful information.

Communication Skills. Too often, scientists and mathematicians do not have a common vocabulary for communicating basic concepts. Ideal team members need the ability to understand each other and to teach each other using familiar terms. They ask good questions and maintain a conversation from a variety of perspectives to advance the common knowledge and to ensure that everyone contributes to solving the problem at hand. In other words, effective team members need to be willing and able to find common ground by breaking down the barriers that separate areas of expertise.

Students (future team members) also need to be able to communicate clearly and succinctly in a variety of formats. They need to be able to report the results of their work in writing at different levels—not only to their peers, but also to non-specialists and non-scientists. Writing skills should be complemented with the ability to communicate data both orally and visually. Presentations enhance communication and often set the framework for more detailed written reports. They frequently require a variety of visual aids that require experience to use effectively. Finally, students need to learn how to match the technical details of a presentation with the ability of the audience to grasp such details. There is no substitute for practice: students need to give presentations early and often.

Teamwork. Teamwork means more than just two or more investigators working side by side on different aspects of a problem. Rather, research teams will be composed of those who can bring their expertise to the problem, communicate with one another about that expertise, and work together on moving a problem forward. Clearly, team researchers do not have to know every fact or every discipline in depth, but they will need to know how to actively engage the expertise of the others each step along the way. One of the key benefits of having students work in teams is to allow them the opportunity to learn to be a team player in an academic setting. They must be able to cooperate, contribute, compromise, and criticize in a way that helps the team.

These are the kinds of skills that will enable individuals with diverse backgrounds and training to collaborate, with each member contributing his/her expertise to a common goal. In the direction the world of biology is heading, where questions of increasing complexity cannot be addressed except by teams with multi-disciplinary skills, the market-place value of the lone individual who solves a problem on his or her own will decrease, while the value of those who are able to work with others on these new kinds of multi-disciplinary questions will increase.

Designing A Renaissance Campus

Assuming we want students to be able to join our renaissance teams as full participants, what academic skills should they develop during their tenure on campus? As importantly, what experiences should they have to equip them for the world outside the academic setting?

Our goals are clear: to provide undergraduates in biology, mathematics, and computer science with opportunities (a) to learn deeply in at least one discipline and broadly in one or two others; (b) to develop their abilities to communicate and work closely with their peers from different disciplines; and (c) to experience the challenges and scientific benefits of interdisciplinary learning.

The challenges are also clear: The segregation of disciplines into different departments (even different administrative colleges) is inherent in the structure of universities. As anyone who has tried to establish an interdisciplinary course can confirm, it is exceedingly difficult (although not impossible) to bring faculty together to cooperatively teach a course. It is even more difficult when such a course requires listing in multiple departments because then questions are raised about which faculty member gets credit for the class, which department gets credit for the student enrollments, etc. For that reason (and many others), faculty are often discouraged from organizing or participating in such cross-disciplinary courses.

Yet if the goal of education is to focus on the student, what we really need are administrative structures to make such courses not only possible, but routine. Change can take a variety of forms, but if the goal is for universities to become more student centered—and if as we have argued cross-disciplinary experiences are in the best interests of students—we need to develop programs that help the university better achieve its goals of quality education for all of its students while protecting the intellectual and professional development of faculty (as is now done now through the departmental structure). To this end, we offer several possible alternatives.

First, at the faculty level, all science, mathematics, and computer science faculty need to view their educational practice as more closely aligned with their research practices. Although many faculty members in the sciences routinely collaborate for research within their discipline, fewer collaborate across disciplines, let alone translate that same kind of interdisciplinary environment into their classrooms. Yet if the classroom is not interdisciplinary (or at least open to other disciplines and perspectives), students will learn disciplines in isolation without understanding the depth and breadth of the subject in its real-world context.

To this end, faculty should highlight the unique relationships between disciplines, rather than focus on their distinctions. And, much as they do in their own labs, faculty need to encourage students to collaborate and learn from one another. In many of the sciences, the atmosphere of the lab is one which integrates advanced undergraduates, graduate students, postdocs, and senior researchers. However, the integration is usually only in one field. The next step is to welcome students and researchers from other areas and to let them experience the atmosphere of a team approach.

For example, to develop effective ecological forecasts (see Clark et al., 2001) a team would need expertise in the principles of ecology, probability (e.g., random variables, stochastic processes), Bayesian statistics, numerical analysis, and computational science. Participation in such teams as part of their undergraduate experience would be especially helpful for mathematics and computer science majors. Indeed, faculty must move beyond the way they were taught as undergraduate and graduate students to develop more effective methods of instruction. In many cases, their graduate school experiences could provide better models of the kinds of interactions that foster interdisciplinary teaching and learning.

At the university level, department heads and other administrators need to develop new ways to reward faculty. Many faculty report that they would be willing to participate in interdisciplinary courses and become more involved in their teaching, but too often the reward structures do not properly acknowledge their participation. Thus the threat looms that extra time spent on teaching at the expense of research may be held against them when they come up for tenure. As a result, frequently the only faculty who can afford to spend the time needed to experiment with new methods of teaching and learning are tenured, near-retirement faculty rather than the younger faculty who could sustain these kinds of student-centered changes.

The Renaissance Campus cannot emerge without changes at the national funding level where it is important that research support move beyond the principal investigator model. The National Science Foundation (NSF), the National Institutes of Health (NIH), and other funding agencies should acknowledge in their own granting procedures that the "lone ranger" investigator model does not necessarily work in today's complex research environment and that it often takes more than one investigator to make a project successful. While most funding agencies now seem interested in supporting interdisciplinary projects, researchers need to know that this is a serious and long-term commitment.

In mathematics, for example, funding has a long tradition of single investigator projects. As a result, it is very difficult for mathematicians to be funded as part of an interdisciplinary team. However, many of the large state-of-the-art research initiatives in biology now funded by NSF, NIH, and others are interdisciplinary, requiring the project to be headed by three or four collaborating investigators. These projects might be a more relevant choice for interested mathematicians in the future.

Achieving a More Integrated Curriculum

If these barriers could be reduced to enable the university structure to become more student-centered, what kind of educational structure might better prepare our Renaissance team? Do we need to tear down the entire structure of the campus and build anew? Or can we work within the existing structure and try to improve it?

On our Renaissance campus, lower division students would still take introductory courses in biology and other sciences, in mathematics, and in computer science. But think for a moment what it might be like if those courses were designed not just to cover the material needed to take the next course in the discipline, but rather were designed from the outset to introduce some of the ideas we've discussed here. Suppose, for example, that all faculty who taught introductory courses in biology, chemistry, and physics met with their colleagues in mathematics and computer sciences and identified a common theme or two (e.g., global warming or Sudden Acute Respiratory Syndrome (SARS)) that they could introduce into one or two sections of both their lectures and labs? Such themes would emphasize the interdisciplinary nature of science and introduce early on many of the mathematical, computer, and communication skills we have been emphasizing. As students progress through this kind of sequence, they might have opportunities to share labs with students in another science sequence, and together be required to gather data and, drawing on their written, verbal and visual communication skills, make a presentation to their peers.

We also can envision introducing complex real-world problems of local interest in the last quarter or semester of large survey courses. For example, Montana has been subjected to a large number of wildfires, which has intensified the debate between forest ecologists, wildlife managers, and politicians on how best to manage public forests and the human/forest interface. This topic is ideal for students to examine from a variety of perspectives, since it involves everything from predicting fire behavior and protecting public health from air pollution, to managing wildlife and fisheries in over-logged or burned environments. It is likely that each university has similar topics of local interest that could be used to generate projects that would capture the interest and imagination of their students.

By the time students reach their junior and senior years, and are taking more specialized courses in their fields of interest, our Renaissance campus would require that they participate in at least one independent research project, ideally with other students from different disciplines. They also would be required to write up and present their research, either in a classroom setting or campus-wide undergraduate research symposium, or both. A number of avenues exist on most campuses to accommodate this kind of interdisciplinary research experience. For example, many campuses have introduced undergraduate research opportunities in which students work in a lab for a summer or a semester. This requirement would simply formalize what is often an otherwise informal learning experience. Another alternative would be to fit it within the existing "independent study" format, although we would prefer to rename it "interdisciplinary study" and would like to see at least two faculty members and at least four to six students from different departments participate in each one. However it is woven into the academic infrastructure, we believe that all students should have at least one research-like experience working on an open-ended, "real-world" problem before they graduate.

These are modest proposals that could readily work within the existing structure of most colleges and universities (and indeed are already happening at some institutions around the country). One of many examples that illustrate this approach is the Center for the Study of Institutions, Population, and Environmental Change (CIPAC) at Indiana University, whose mission is to understand how and why some forests are fragmented, degraded, and losing species, while other forests are in good condition and even regrowing and expanding. This long-term study (Dietz et al. 2003) involves environmental scientists, geographers, political scientists, satellite imaging experts, computer scientists, statisticians, and students at all educational levels.

For these programs to work and become more common, we will need to radically change the focus of the university as a faculty-centered research and teaching environment where students come to be taught, to one that is known for being student centered, where students participate in research and come to learn. Dcspite widespread belief to the contrary, there is a natural and important connection between teaching and research. Faculty engaged in creative research endeavors can bring the excitement of discovery and up-to-date scientific advances to the courses they teach. Active faculty researchers can model science as a human endeavor, involving diverse people in traditional and nontraditional carecr settings (AAAS, 1990). Moreover, they can model and foster rigorous critical thinking, originality, creativity, and problem solving with students at all levels of educational experience, as well as in diverse educational settings.

The Renaissance Campus would benefit all students, even those who do not go on to become members of biological research teams or biotech industrial groups. Graduates of such a campus will have developed skills that ensure that they can think critically, communicate with others, and be intellectually flexible in whatever career they do pursue. As important, they will have developed the skills they need as citizens to look at questions of local, national, and global concern, and make informed decisions that can potentially affeet us all.

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