The Reciprocal Relationships Among Research, Teaching, and Learning

Leader: Robert J. Full, Chancellor's Professor of Biology, Co-Director of the Center for Interdisciplinary Bio-Inspiration in Education and Research, Department of Integrative Biology, University of California at Berkeley

Recorder: Simon Sponberg, Doctoral Candidate, Department of Integrative Biology, University of California at Berkeley

Presentation

Although it has been eight years since publication of the Boyer Commission report (1998), challenges remain in reinventing undergraduate education at research universities. Today's innovative companies want employees who can lead interdisciplinary teams to take creative approaches in solving problems, critically interpret and analyze results, infer general principles, predict future outcomes and challenges, and clearly communicate their findings. These are the skills that define education in a new age of integration. As massive amounts of information are becoming globally and instantaneously accessible, the demand is for graduates who can synthesize and creatively apply these resources to problems at hand. The fact that this skill set coincides exactly with that of a research scientist underscores the unique potential research universities have to educate and produce graduates with these skills. Unfortunately, just when their skills would be most advantageous for today's students, many of our best researchers are doing less teaching (National Academies, 2004). As a result, creative approaches to training undergraduates in critical thinking are lacking (Black, 2003).

To accomplish a reinvention of undergraduate education we must bring attention to the value of interdisciplinary, collaborative teaching. We must move away from teaching students as encyclopedias with partitioned sets of facts delivered in a traditional lecture context with no critical thinking requirements. We need to transition from the department-based, campus-centric view of education and research as distinct and separate towards and integrative, global reaching academia with topic-based courses blurring the lines between research and teaching. Enabling this transition requires creating novel courses, implementing inquiry-based pedagogy and redesigning teaching spaces.

However, this reinvention foremost demands the efforts of engaged research professors who can inspire inquiry. Recommendations to motivate research professors to engage in redesigning curricula include rewarding innovative teaching through the tenure process and increasing funding for curricular innovation (National Research Council, 2003). While praiseworthy, changes resulting from such initiatives have been hard to realize, largely because teaching is still considered of secondary value to academic success at research universities. Yet interdisciplinary teaching can present a unique opportunity to directly benefit the research of the faculty member who seeks to redefine education. In a truly interdisciplinary framework, teaching and research are synergistic.

To demonstrate these ideas in practice, we will report on four courses that were developed and implemented in the Department of Integrative Biology at the University of California at Berkeley (http://ib.berkeley.edu). Together they create the foundation for making shared discoveries in a synergistic teaching and research setting (Figure 1). These course designs follow frameworks for training critical thinking processes. We emphasize the importance of training tools for learning rather than specific pieces of information. Following Lett (1990), the most critical of these are falsifiability, logic, comprehensiveness, honesty, replicability, and sufficiency. Not surprisingly, these are also the core principles of innovative research and academic inquiry. Students emerging from courses emphasizing these principles should be prepared to ask probing questions, define problems, examine evidence, analyze assumptions and biases, avoid emotional reasoning, resist over-simplification, consider other interpretations, and tolerate uncertainty (Wade and Travis, 1990). Finally, treating students as researchers and faculty members as research mentors moves the students along a path of personal discovering, realizing concepts new to themselves, until ultimately attaining a universal discovery.

1) Teaching Laboratory with Personal Discovery (*Upper-division majors lab course*): *Small teams of students rotate through structured, but not "cookbook" multidisciplinary labs that culminate in independent investigations that require students to formulate, research and defend their own discoveries.*

We have implemented this framework in a comparative physiology lab course. Twenty-five students break into collaborative teams and participate in three rotations through lab stations spending 3 weeks in each rotation.. This rotation framework maximizes equipment usage and enables the students to have direct experience with equipment that might be too expensive or require too much supervision for an entire class to use simultaneously. Each set of rotations also introduces students to a specific set of interdisciplinary techniques from engineering, computer science, and statistics (Figure 2).

Comments from students' papers throughout the course reveal their progress in critical thinking. When faced with data that were not entirely consistent with their expectations, students first claimed, "my data are bad or wrong" or "the lab project does not work." Later, as they investigated the literature, they began to relate their discoveries to the work of others. They reported, "well, Smith (1988) said I should have found this…" or "my data are inconsistent with Smith (1988)." Finally, as they had experience working with open-ended labs where specific results were not predetermined, they began to critically analyze the literature and their own data. The final papers reveal this ability: "Smith (1988) reported this, but did not consider this factor, so we …"

This progression in thinking parallels the models of Perry (1970) and Nelson (1989) (Figure 3). Students initially consider information in terms of right and wrong relying on authority to deliver the truth. Realizing uncertainty is real, they develop a personal truth, but feel all answers are valid. Realizing opinion is insufficient, they begin to provide evidence for different hypotheses. Finally, realizing that personal evaluation is needed to develop a defendable, evidenced hypothesis, they state alternatives, are skeptical of unsupported statements, and accept responsibility for their positions.

The course culminates in independent projects that require these skills. Importantly, students formulate questions about what is not known and these explorations can lead to true universal discoveries, often in unexpected ways. For example, it is known that gecko's have unusually low energetic costs for locomotion compared to other animals. The mechanism for this difference is unknown. Graduate student lab instructors first had the students measure the metabolic rate of geckos, which were found to be lower than predicted from other animals. Students were then guided in reviewing the literature and discovered that temperature is an important factor governing metabolic rate in ectotherms. The next lab session the students repeated their measurements on geckos while controlling temperature. This explained some of the energetic difference, but not all.

Seeking to understand this surprising result, one group of students pursued an independent investigation into the topic for their final project. They suggested that the curious manner in which geckos stick to surfaces and then peel their toes away could explain the lower energetics. As is often the case in research, they ultimately did not answer the question they originally set out to address. However, their work did uncover that the adhesive of a gecko is made up of many dry, finely branched hairs. Since no other adhesive of this type was know at the time, one of the graduate student instructors and one of the students continued this research which ultimately led to the discovery that van der Waals forces, the weakest intermolecular forces, were responsible for adhesion of gecko hairs (Autumn *et al*., 2000; Autumn *et al*., 2002) This discovery has inspired the design of artificial gecko adhesives that are now being incorporated into a novel legged climbing robot. The undergraduate involved in this research, Tonia Hsieh, has gone on to graduate and ultimately PhD work at Harvard University in animal biomechanics.

2) Research-Based Symposium Class *(Upper-division majors course): After lecturing about core concepts for the first half of the course, the instructor breaks students into teams whose members must present, in scientific symposium style, a primary journal article as if they were contributing authors.*

We implemented this course design in a 90-student junior and senior level class on comparative physiology. The lecture content of the course was reduced and consolidated into the first half or two-thirds of the semester. The content was the same as the non-symposium version with respect to the principles taught, but the number of specific examples was reduced. Groups of four to five students were then responsible for presenting during the remainder of the class session. Each group had to delve into the scientific literature to find interesting articles that related to the major topics of the class. After choosing one primary article and approving the article with us, students presented the paper before the rest of the class as if they were co-authors on the study. They were responsible for presenting the necessary background material for general comprehension, clearly reporting and interpreting the results, and critically addressing any limitations or conflicts within the study.

Equally important to the students presenting, those listening to the symposium talks were each required to turn in a question about each presentation. The best questions appeared on the final exam. This encouraged critical listening, promoted an active discussion period, and challenged both the listeners and presenters.

We found that students began to adopt a "we can do that" attitude towards research by directly involving themselves in the presentation of real research results. Several of these students have taken ideas that were sparked by the papers they presented and gone on to successful research in academia and industry. Anna Ahn, now a professor at Harvey Mudd College, realized the limitations of looking at muscles simply as motors and has gone on to demonstrate that very similar muscles can perform quite diverse functions acting not only as motors, but also struts and even brakes (Ahn and Full, 2002 http://www.biology.hmc.edu/people/faculty/ahn.html). Building on these biological results, Marcus Rosenthal, another former Berkeley biology student, is developing the next generation of artificial muscles while working for the biotech company Artificial Muscle Incorporated a spin-off of SRI International (http://www.sri.com).

3) Research-Based Project Class *(Lower-division non-major course)*: *A diverse group of students is presented with scientific topics that have relevance across many areas and then form cross-disciplinary teams to engage in projects using toys to propose and defend designs for the next biologically inspired robot for extra-planetary exploration.*

Teaching critical thinking skills need not be limited to juniors and seniors. General major courses provide the foundation for beginning scientists and are often the only encounter with scientific discovery for non-science majors. We have developed a lower division class that is project-based without a distinct laboratory component. Initially, this course was taught simultaneously to both undergraduates at UC Berkeley and a local 6^{th} grade public middle school science class.

In this course called Biomotion, lectures focus on specific examples from biology, engineering, art, and medicine exemplifying the core concepts of biological locomotion, biological inspiration, and biomechatronic design (Figure 4). For the last third of the course, students work on bio-inspired design teams during discussion sections run by graduate student instructors. The task of these teams is to use biologically jointed toy design kits (Zoobs) to construct prototypes for the next bio-inspired robot explorers to search for extraterrestrial life. While built with toys, these are not toy designs. Students are required to apply concepts they have learned from class as well as their own review of the literature. Many of these manufacturing techniques and devices are so new that they do not yet appear in engineering design classes. Projects culminate in a presenters' forum night. This forum is run as a poster conference where each student team creates a company or academic center and must defend their project ideas and prototypes to a granting review body, composed of professors and graduate students who evaluate their work.

Students must take ownership and responsibility for their projects. This generates remarkably creative ideas. In fact, many of the best teams are composed not of four engineering or science students, but rather a diverse mix of students from different fields. Overall, students find they can create truly novel designs arising from a critical understanding of basic principles of motion in biology This inspiration need not be limited to specific fields. Ed Chen, a biomotion alumnus, has gone on to work at Pixar in designing animated films. Understanding of the basic running mechanics of cockroaches and humans inspired much of movement animation in the film *A Bug's Life* (http://www.pixar.com/featurefilms/abl). In engineering, Naomi Davidson went on to complete graduate work at MIT after building a swimming robot inspired from fish locomotion in the class and then a real version in the engineering department at UC Berkeley.

4) Introductory Biology Research Lab *(voluntary field sections): Graduate students lead introductory biology labs in which 20- to-30 students, working at one of several off-campus field sites, design and conduct field experiments on guided research questions.*

In a large general biology class, students can choose to do alternative field research-based labs rather than the general course lab. Both graduate student and faculty field researchers inspire the students in designing and executing projects that are spin-offs of the professors' field programs. Graduate student instructors lead the teams of students in the field and supplement the independent projects with demonstrations of ongoing field studies at several of the University of California reserves and regional wild lands. Students gain not only an early appreciation for scientific methods, but also awareness of the biodiversity in local environments around Berkeley. For many students, this is a formative experience that will shape future biology course work and undergraduate dissertations (Figure 5).

Our experience with these courses has made it clear that research-based teaching inspires teaching-based research. Students become more capable researchers through the integration of research-related exercise and pedagogy that emulates research methods and practices. The graduate students and postdoctoral fellows who participate in the teaching generate new research ideas and are better able to communicate with interdisciplinary collaborators. Undergraduates who have taken these courses and gone on to further study have facilitated the transfer of concepts and resources to develop new fields, form industrial partnerships, and engage in interdisciplinary research teams. In an effort to promote this reciprocal relationship, a new Center for Interdisciplinary Bio-inspiration in Education and Research (CIBER) is being inaugurated at the University of California at Berkeley (Figure 6). The mission of this center is to innovate methods to extract principles in biology that inspire novel design in engineering and train the next generation of scientists and engineers to collaborate in mutually beneficial relationships.

Discussion

Despite the optimism that these specific examples of integrating teaching and research inspire, those interested in promoting and conducting interdisciplinary teaching and research face daunting challenges. Breakout group members first discussed concerns about the design and implementation of interdisciplinary courses with Professor Full:

Breakout Panelist: The courses you suggest seem to have a large teaching responsibility. How do you manage your time to provide the students with sufficient assistance and still carry out what sounds like a diverse and quite large research program?

Professor Full: There is definitely a challenge in managing the time these classes can take. I still do lecturing, which has a relatively known time investment once you have a set of lectures created, but most importantly I specifically set aside time which I spend dealing with course issues, answering students' e-mails, and holding office hours. I use office hours very effectively to work with groups. I make it clear that outside of these times I am not available for teaching responsibilities and I hold carefully to this time commitment. Also having good graduate student instructors can remove some of the time responsibility from the professor.

Breakout Panelist: Is the common lab space that you have set aside at Berkeley part of someone's lab? There seems to be an institutional barrier to establishing a joint research and teaching lab, since funds tend to be allocated specifically and exclusively for either teaching or research.

Professor Full: The common lab space is part of CIBER and separate from any individual's research space. Researchers still need a space exclusively to do research, but this new space has a dual-use purpose for research and teaching. It is effectively putting them side-by-side. Add to that a library unit on the same floor with dedicated rooms for learning how to do literature searches and you have a seamless suite with all the components necessary for inquiry-based education. Students no longer see teaching, research, and library work as separate. To accomplish this design, you can simply ask faculty members what they want to do in particular classes and build the space around that. Fortunately, faculty at Berkeley had input in the redesign of our current building and this has worked quite well.

Breakout Panelist: With the gecko project that you mentioned earlier, how much did you know before going into it?

Professor Full: Personally? Nothing! And I still do not know the answer to that question.

Breakout Panelist: So you just threw it out there to the students?

Professor Full: Yes, I mean, we knew that geckos exhibit lower energy consumption than other animals and we had the students demonstrate this in lab, but I knew nothing about the mechanism. Ultimately, the students picked-up on the question and ran with it. In the end, even though they did not resolve the original question about low-cost energetics, their investigation prompted the discovery of the gecko's remarkable ability to stick and led the graduate instructor for that course to take on this project as a major part of his dissertation and post doc research.

Breakout Panelist: You mentioned that about a third of your course goes through the independent projects or symposium, how do you determine which students participate?

Professor Full: I meant I spend a third of the course *time* on these projects. I do lecture for some of the early parts of the class, but more to provide the students with the concepts and big picture rather than covering a specific content set and many examples..

Breakout Panelist: You mentioned that you taught one of your c courses at the same time to both undergraduate and 6th grade students. I am curious about how the 6th grade class went.

Professor Full: This is really stressful. First, it did not fit under No Child Left Behind and other standards, so I had to write a very long proposal to defend why the course was a good idea. I do not want to get into that now as it is a topic of contention, but I will say that I did run the courses together at the same time, although it nearly killed me. I ran it in three modes. I did it in a lecture mode where I gave really exciting lectures with fun videos and then we had a little symposium where they had to tell me what they knew. I did it in an experiment mode where it is like a teaching lab. We had the students measure animals as they flew or ran or crawled, but there was a principle behind it that we wanted them to learn. The students really enjoyed this. Finally, I ended with a project mode where the students had to create the robotic explorers. I had them present their designs to the rest of their school and they did very well.

The results of these approaches were clear. They did the worst on the lecture, which breaks my heart. They did not do that well in the experiment mode, which bothered me, although they liked it the most. They did not really learn the underlying principles. In terms of understanding and development, they did the best on the project mode because of the critical thinking model and the constructivist approach. The idea being that they took the project on as their own and, as a result, put in much more work than they would have otherwise. They were much more inspired and driven while doing the project. My conclusion from these courses was that before I was not giving them what they needed to express their creativity and thinking ability. Students are incredibly good. You just need to not put them in a mode that crushes this creativity and fails to award critical thinking.
(http://polypedal.berkeley.edu/twiki/bin/view/PolyPEDAL/Oak_Grove/OG_home.html)

Breakout Panelist: We also need to think about placing these students into internships and out in the community where they can learn these skills in more of a real-world environment. When they go out into government or industry, they face stricter requirements regarding inquiry and experience.

Professor Full: Yes, I think we need to do more of this. Also we need to expand our focus into more service learning.

Following this general discussion, we split the breakout session into sub-groups to address one of three core challenges concerning the implementation of research-based teaching and teaching-based research. Each group used three specific questions to prompt discussion and then reported back recommendations for each topic.

Group 1: Best Practices & New Approaches

- What other research-based formats have been successful?
- What are the major limitations to a research-based approach in the classroom?
- What novel approaches might be attempted?

Group 2: Promoting Institutional Change

- What are the barriers to offering research-based courses or curriculum?

- What technologies/structures/facilities/funding need to be developed to promote integration of research and teaching?
- What type of faculty reward structure needs to be implemented?

Group 3: Assessment

- What are the limitations of current assessment tools for research-based approaches?
- What types of assessment tools can measure the value of research-based approaches?
- How can longitudinal assessments be accomplished, since the effect goes far beyond the end of the course?

Each group provided a reporting out of their discussion and a specific recommendation critical to addressing their challenge (see Recommendations).

<u>Summary discussion points</u>

- As the multidisciplinary framework underlying the group's discussion suggests, the ideas promulgated at the session should not be limited to biology or even science alone. These ideas can, and indeed must, be applied generally to high enrollment classes that are endemic at research universities.

- The symposium- and project-based classes were successful in settings with 60-100 students. Teaming graduate student instructors with small groups of undergraduates can facilitate inquiry-based learning in even the largest classes.

- Teaching *content* is always an issue. We must provide our students with the core concepts of the field, but information is increasing so rapidly that we often must give up or off-load specific detailed content to provide opportunities for inquiry- and research-based learning.

- For faculty members, the development of innovative curricula takes a great deal of time. To prevent research from suffering, one can develop courses incrementally over several years and specifically limit the time one is available during the semester.

- A frequent impediment to implementing research-based courses is the lack of equipment and space. One way to address this problem is to designate a common teaching-research lab space independent of individual professors' laboratories. This approach has worked successfully with CIBER.

Recommendations

- <u>Promoting Interdisciplinary Study</u>: To facilitate new course designs, every department or program should be required to establish at least one interdisciplinary inquiry- or research-based course that is required of all students in that major. Developing new courses will be challenging, particularly for new faculty members. We need to make use of pre-existing systems and resources, like graduate students, to facilitate taking on students as agents of learning and research.

- Rewarding Change: To promote institutional incentives for novel research-based teaching, tenure and promotion guidelines should define *research* broadly to encompass interdisciplinary teaching endeavors. Institutions should recognize that faculty members who successfully implement research-based teaching, particularly across fields, are often contributing to their research success.

- Assessment**:** To determine the impact of inquiry- and research-based, we recommend the development of a set of *best practices* for assessing undergraduate research-based approaches including strategies and tools (e.g. students portfolios) that can be used in diverse learning environments. While challenging to formulate, we must develop both short- and long-term identifiable student outcomes for these specific course designs.

Printed Materials

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Websites

Center for Interdisciplinary Bio-Inspiration in Education and Research (CIBER):
http://ciber.berkeley.edu
Department of Integrative Biology, the University of California at Berkeley:
http://ib.berkeley.edu
Robert J. Full:
http://polypedal.berkeley.edu
SRI International:
http://www.sri.com
Anna Ahn:
http://www.biology.hmc.edu/people/faculty/ahn.html
Pixar:
http://www.pixar.com
Oak Grove Middle School:
http://polypedal.berkeley.edu/twiki/bin/view/PolyPEDAL/Oak_Grove/OG_home.html