



## SYMPOSIUM

### Interdisciplinary Laboratory Course Facilitating Knowledge Integration, Mutualistic Teaming, and Original Discovery

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From the symposium “Leading Students and Faculty to Quantitative Biology Through Active Learning” presented at the annual meeting of the Society for Integrative and Comparative Biology, January 3–7, 2015 at West Palm Beach, Florida.

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**Synopsis** Experiencing the thrill of an original scientific discovery can be transformative to students unsure about becoming a scientist, yet few courses offer authentic research experiences. Increasingly, cutting-edge discoveries require an interdisciplinary approach not offered in current departmental-based courses. Here, we describe a one-semester, learning laboratory course on organismal biomechanics offered at our large research university that enables interdisciplinary teams of students from biology and engineering to grow intellectually, collaborate effectively, and make original discoveries. To attain this goal, we avoid traditional “cookbook” laboratories by training 20 students to use a dozen research stations. Teams of five students rotate to a new station each week where a professor, graduate student, and/or team member assists in the use of equipment, guides students through stages of critical thinking, encourages interdisciplinary collaboration, and moves them toward authentic discovery. Weekly discussion sections that involve the entire class offer exchange of discipline-specific knowledge, advice on experimental design, methods of collecting and analyzing data, a statistics primer, and best practices for writing and presenting scientific papers. The building of skills in concert with weekly guided inquiry facilitates original discovery via a final research project that can be presented at a national meeting or published in a scientific journal.

#### Introduction

The President’s Council of Advisors on Science and Technology Report, *Engage to Excel* (2012), urged that educators “advocate and provide support for replacing standard laboratory courses with discovery-based research courses.” Recommendations to involve students in authentic research during the academic year from our most influential organizations could not be more prevalent or persistent (Kenny et al. 1998—Boyer Commission Report; National Research Council [NRC] 2003a, 2003b—BIO2010; Association of American Medical Colleges and the Howard Hughes Medical Institute 2009; NRC 2009; American Association for the Advancement of Science 2011; Association of American Colleges and Universities 2013). A Convocation at the National Academy of Sciences on “Integrating Discovery-Based Research into the Undergraduate Curriculum” sponsored by the Board on Life Sciences and Science

Education of the National Research Council was held in May 2015 with the report due out in the fall. In concert, and just as insistent, is the call to facilitate interdisciplinary research (IDR) and foster its development in education (National Academy of Sciences [NAS] 2004; NRC 2010, 2014, 2015; American Academy of Arts and Sciences [AAAS] 2013). Here, we describe a one-semester, interdisciplinary, learning laboratory course that we began to develop at the University of California at Berkeley in 2007 and have now taught for 8 years. In addition to the course structure, we describe the themes of our pedagogical framework which encourages interdisciplinary teams of students to grow intellectually, collaborate effectively, and make original discoveries. Finally, we provide preliminary evidence of students’ learning and pose a developmental construct (Wilson and Scalise 2006) for assessing interdisciplinary skills in higher education.

## **Authentic discovery in course-based research experiences**

One goal of our learning laboratory is to provide students with the thrill of original discovery. Therefore, we must go beyond the traditional “cookbook” laboratories where confirmatory experiments are described in a manual that is to be followed step-by-step to get a right answer. Our laboratory also differs from inquiry-based laboratories where students define their own problems, design experiments, generate and analyze data, but only share their findings with the class for educational purposes because the findings do not necessarily advance the field. In authentic discovery-based courses, students conduct research where they make an original intellectual or creative contribution to the discipline (National Science Foundation 2003) using the “. . . mentor’s expertise and resources, the student is encouraged to take primary responsibility for the project and to provide substantial input into its direction” (Cartrette and Melroe-Lehrman 2012). Russell and Weaver (2011) “suggest that laboratory curriculum is a strong factor in the development of students’ discussions of theories and their conceptions of creativity in science. Students in the research-based laboratory curriculum demonstrated the most gains as a result of their laboratory when compared with their counterparts in the traditional and inquiry-based laboratories.” They conclude that, “Students in research-based laboratories outperform the traditional and inquiry students in terms of their development of deeper understandings of the nature of science” and “students in the research-based curriculum more often developed sophisticated conceptions of the nature of science than students in either the traditional or inquiry-based cohorts.” Although far more work is needed to directly measure gains in capabilities to conduct research, course-based research experiences may benefit from the opportunities to develop conceptual understanding by greater integration with lectures, discussions, and reading materials than may be provided in a faculty member’s research laboratory alone (Linn et al. 2015).

## **Facilitating interdisciplinary teaming in teaching laboratories**

The AAAS (2013) warned that research is at a tipping point in a transition from ultra-specialization and highly prescribed problems to one in which integrative and collaborative approaches are required to solve complex challenges (NRC 2014). The NAS (2004) defined IDR broadly as “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 or to solve problems whose solutions are beyond the scope of a single discipline or field of research practice.” In 2004 the Committee on Facilitating IDR recommended that “undergraduate students should seek out interdisciplinary experiences, such as courses at the interfaces of traditional disciplines that address basic research problems, interdisciplinary courses that address societal problems, and research experiences that span more than one traditional discipline . . .” and that “educators should facilitate IDR by providing educational and training opportunities for undergraduates, graduate students, and postdoctoral scholars, such as relating foundation courses, data gathering and analysis, and research activities to other fields of study and to society at large.” The National Research Council’s report on *Enhancing the Effectiveness of Team Science* (2015) adds that, “There are few opportunities to learn to collaborate effectively or understand science as a social and intellectual process of shared knowledge creation. . . At the undergraduate level, students majoring in science and the related STEM disciplines take courses dominated by lectures and short laboratory activities that often leave them with major misconceptions about important disciplinary concepts and relationships.” In 2003, the National Research Council advocated that “laboratory courses should be as interdisciplinary as possible, since laboratory experiments confront students with real-world observations that do not separate well into conventional disciplines.” Recent reports suggest to “expand education paradigms to model transdisciplinary approaches” (AAAS 2013) encouraging convergence. “Convergence is an approach to problem solving that cuts across disciplinary boundaries. It integrates knowledge, tools, and ways of thinking from life and health sciences, physical, mathematical, and computational sciences, engineering disciplines, and beyond to form a comprehensive synthetic framework for tackling scientific and societal challenges that exist at the interfaces of multiple fields” (NRC 2014).

Significant progress has been made on incorporating interdisciplinary approaches in higher education (Petrie 1992; Gouvea et al. 2013; Knight et al. 2013; Thompson et al. 2013) and defining the challenges of team science (Kozlowski and Ilgen 2006). We learned from these best practices, and then added a dimension by reflecting on, examining, and articulating successful and unsuccessful models of

interdisciplinary collaboration within our own research programs. For over 20 years, three of us have been members of numerous large interdisciplinary grant programs. We have observed best practices for interdisciplinary teaming, as well as those that failed. Over the 8 years during which we have developed the learning laboratory, we have tried a variety of approaches to best facilitate interdisciplinary teaming derived from solving the many challenges we faced in our own collaborations in research. These barriers included: lack of common basic knowledge, non-overlapping sets of skills, divergent styles of thinking and assumptions, discipline-specific language barriers, discipline-superiority issues, and varying notions of leadership in group dynamics (NRC 2015).

### **Mentoring students to think like research scientists**

At least three challenges need to be met if students are to make an original, interdisciplinary discovery in a single semester. First, students are not yet experts in any single discipline; therefore, they require a form of apprenticeship learning (Feldman et al. 2013). Second, college students must, “undergo a developmental progression in which they gradually relinquish their belief in the certainty of knowledge and the omniscience of authorities and take increasing responsibility for their own learning” (Felder and Brent 2004). Third, time is extremely limited in course-based experiences in research.

Studies demonstrate that the duration of a research experience significantly affects outcomes (Sadler et al. 2010; Adedokun et al. 2014; Shaffer et al. 2014; Linn et al. 2015). During the first year, undergraduate researchers gain familiarity with techniques of the laboratory, but rarely acquire the higher-order intellectual skills such as those used by expert scientists to originate and complete a research study (Feldman et al. 2013). Thiry et al. (2012) found that adopting the traits of scientific researchers such as patience, perseverance, and initiative begins to emerge in the third semester of a research experience. Feldman et al. (2013) concluded that “it is unlikely that in 4–10 weeks a novice researcher will gain the methodological and intellectual proficiency needed to become a knowledge producer.” We overcome this limitation through scaffolding apprentice learning to accelerate the trajectory of intellectual growth necessary for original discovery. The structure of our learning laboratory exposes student teams to a diverse cadre of mentors that include faculty, experienced graduate student teaching

assistants, and graduate and undergraduate student peer mentors that emerge within a team. Even though students lack the expert disciplinary knowledge to contribute to an interdisciplinary team, they can receive sufficient knowledge through Just-In-Time teaching techniques from mentors at the beginning of each laboratory and at critical stages during the laboratory experiences (Lopatto 2010). For structured laboratories, mentors incrementally advance their team to near-original discovery each week, thereby preparing them for the final project that demands a novel discovery.

Students begin our laboratory with preconceived notions that authentic research is a solitary activity which closely resembles a traditional “cookbook” laboratory where they must find the right answer (Cartrette and Melroe-Lehrman 2012). To complement their acquisition of laboratory skills and disciplinary knowledge, our mentors attempt to guide students from dualistic, right-or-wrong thinking or opinion, to the justification and defense of a scientific assertion. “Kroll (1992) describes intellectual growth as the progression from ignorant certainty to intelligent confusion” (Felder and Brent 2004). We achieve a degree of epistemological development with guidance from our simplified version of the Perry Model of intellectual and ethical development focused on critical thinking (Perry 1970), but are cognizant of further research on reflective judgments of claims of knowledge (Baxter Magolda 1992; King and Kitchener 1994; Felder and Brent 2004).

By sharing the thrill of original scientific discovery with students through the development of their ability to think critically and creatively, solve problems, innovate, communicate, collaborate, and to work in interdisciplinary teams, we prepare them for the future because twenty-first-century skills most closely resemble those of a researcher (Fig. 1).

### **The structure of our laboratory course in discovery-based learning**

We contend that an interdisciplinary approach to research in science and engineering must be taught explicitly. To this end, we created a laboratory course in discovery-based learning called the “Mechanics of Organisms Laboratory.” The course is offered in our interdisciplinary Center for Interdisciplinary Biological-inspiration in Education and Research (CiBER)—founded at the University of California, Berkeley in 2005. The center is composed of 35 faculty members from across the campus representing eight different departments from biology and engineering and two from the Natural History Museums.

### Critical Thinking and Problem Solving

- Reason effectively - logic as a language
- Use Systems Thinking - analyze how parts of a whole interact with each other to produce overall outcomes in complex systems
- Make judgments and decisions with massive amounts of data available
- Solve complex problems with unconventional, innovative approaches

### Creativity and Innovation

- Think creatively - use a wide range of idea creation techniques
- Work creatively individually and in collaborative networks
- Demonstrate originality and inventiveness
- Embrace change
- View failure as an opportunity to learn

### Communication and Collaboration

- Communicate ideas effectively, efficiently, broadly through collaborative networks
- Utilize multiple media and technologies, and know how to judge their effectiveness
- Collaborate effectively and respectfully with diverse teams
- Exercise flexibility and willingness to compromise to accomplish a common goal
- Assume shared responsibility for collaborative work, and value the individual contributions made by each team member

### Interdisciplinary Thinking

- Apply knowledge, attitudes, behaviors, and skills across disciplines in appropriate and effective ways

**Fig. 1** Interdisciplinary skills for the twenty-first century. From Museums, Libraries, and 21st Century Skills (2009). (This figure is available in black and white in print and in color at *Integrative and Comparative Biology* online.)

CiBER serves as a common laboratory for sharing ideas among disciplines, making original discoveries, and training the next generation of interdisciplinary researchers and educators. The common laboratory holds state-of-the-art research stations that provide the opportunity for original discovery both in research and in teaching.

### Mentors

The learning laboratory is structured so that students necessarily interact with mentors at various stages of their scientific development. Two to three faculty members, one or two experienced graduate student teaching assistants, and graduate and undergraduate student peer mentors within a team serve as mentors for a class of 20 students. Each team is led by a faculty member or experienced graduate student for each week of a laboratory (Fig. 2). Our layered approach to mentoring that includes faculty and students helps solve the challenge that a course-based research laboratory places on mentors to guide many students (Egan et al. 2013). In addition, Feldman et al. (2013) found that mentoring by graduate researchers tends to focus on technical aspects of experiments, whereas faculty are more likely to assist students in building a scientific identity by articulating their knowledge, underlying theories and concepts, reasoning, problem-solving skills, along with a vision for the direction of the field and the next challenge to approach (Linn et al. 2015). In addition, we have a technical assistant who facilitates

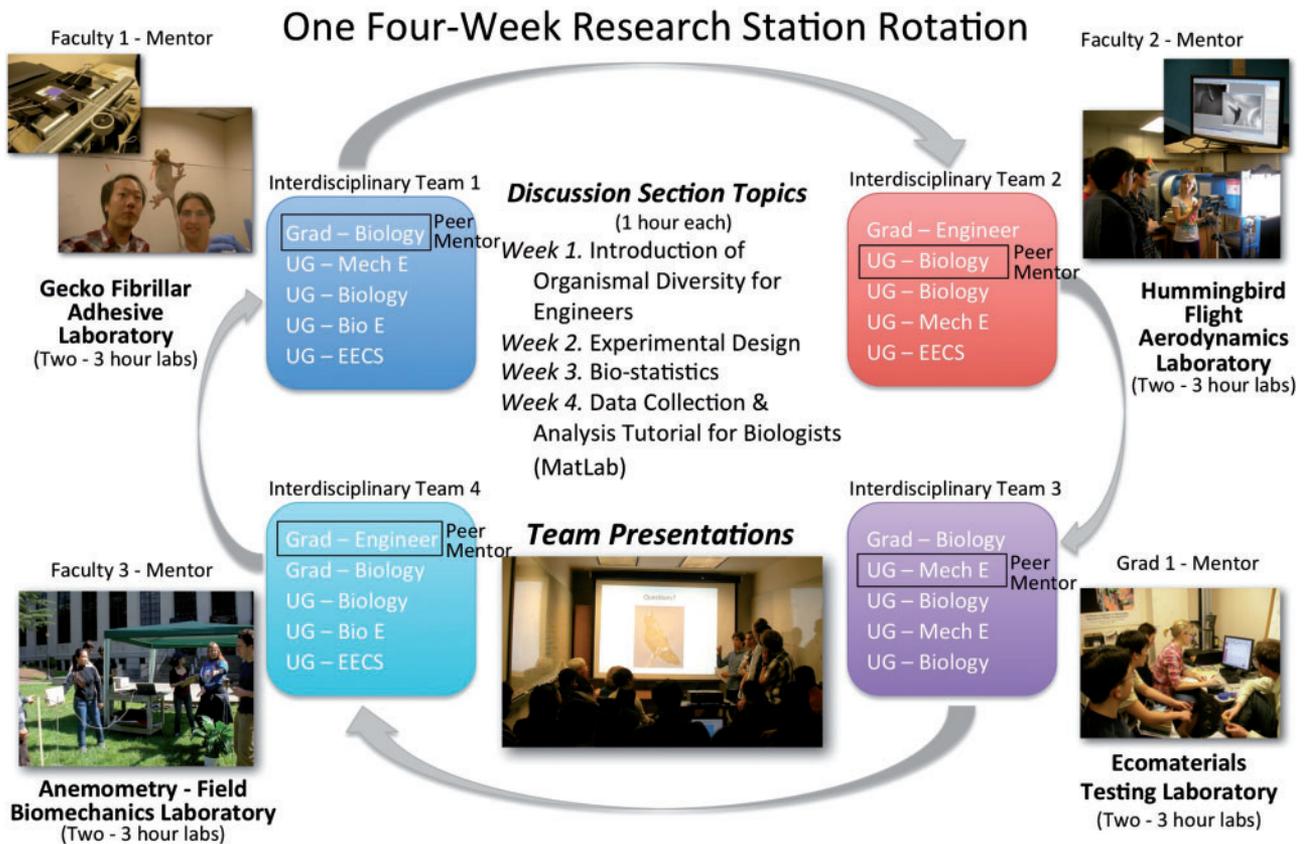
setup and maintenance of all necessary equipment, and also accelerates the learning curve by sharing how we discovered the limits of the equipment through repeated failures when pushing boundaries.

### Interdisciplinary teams

To facilitate interdisciplinary discovery in our learning laboratory, we form diverse teams using demographic and background educational information from a pre-course survey. We compose four teams of four to five individuals each (Fig. 2). We structure the experience of the team by including one to two graduate students and three to four undergraduates who are juniors or seniors. Typically, we balance the number of biologists and engineers in each team so that the number of organismal and environmental biologists match the number of mechanical, electrical, computer science, and bioengineers (two to three for each team). In the past few years, we have been able to balance gender within teams (two to three women per team). We strongly encourage biologists to share their understanding of living systems with engineers and engineers to explain the value of their skills and quantitative abilities in mechanics to biologists.

### Rotations to diverse research stations

Every team experiences two 3-h laboratories at one research station per week, each associated with a given technique and challenge detailed in a handout available before the laboratory (see Supplementary



**Fig. 2** Example of one 4-week rotation of discovery-based learning laboratory. Four laboratories using state-of-the-art research equipment are set up and run each week for 4 weeks (shown in four corners). Each laboratory is mentored by a faculty member or graduate student mentor for two sessions during the week for 3 h per session. Four interdisciplinary teams are composed of five students with diverse expertise in Biology and Engineering (Bioengineering—BioE, Electrical Engineering and Computer Science—EECS, and Mechanical Engineering—Mech E). Teams usually have at least one graduate student (Grad) taking the course along with three to four undergraduates (UG). Peer mentors informally emerge in the team (Black rectangles). Teams rotate to the next laboratory after the week concludes (arrows). A 1-h discussion section led by faculty covers critical topics for interdisciplinary integration. Teams select one of the laboratories to present as if at a professional society meeting. This format is repeated for eight new experiments in two more rotations before students begin their independent project. (This figure is available in black and white in print and in color at *Integrative and Comparative Biology* online.)

Material). In one rotation, we operate four research stations concurrently per week (Fig. 2). A graduate student teaching assistant or faculty member guides each team by first delivering an opening lecture to pose the challenge, and then uses guided inquiry through direct questioning (Weaver et al. 2008) at each stage of the laboratory. After a team finishes one laboratory in that week, they rotate to a new research station for the following week.

For the semester, we set up a total of three rotations, each comprising four separate stations (Table 1). Our framework of rotation maximizes usage of unique equipment, thus enabling students to have direct experience with equipment that might otherwise be too expensive or require too much supervision for an entire class to use simultaneously. Each research station introduces students to a specific set of interdisciplinary techniques and principles

from biomechanics and engineering. We expose students to diverse species and to different types of laboratory equipment that include the energetics of locomotion by cockroaches running on a treadmill ( $O_2$  analyzer), adhesion by geckos (force transducer), 3D kinematics and dynamics of the running of cockroaches and lizards (high-speed video cameras and force platforms), control of rapid running by cockroaches (electrical monitoring of muscles using electromyograms), stress-strain biomaterials testing of passive muscles of birds, squid muscle, connective tissue, or seaweed stipes along with dynamic stress-strain tests of activated muscles of insects (workloop analyses) using the patterns of loading they experience in nature, hummingbirds' flight in a wind tunnel (particle image velocimetry), fluid mechanics of physical models in a water flume, measurements of flow in nature, and simulations of motion

**Table 1** Mechanics of organisms discovery-based learning laboratory

Rotation	Research station (Laboratories)	Discussion
First (Weeks 1–4)	Muscle Power (Workloops) Neuromechanical Feedback Dynamics of Running Kinematics of Flight	Organismal diversity for engineers Experimental design Bio-statistics Tutorial on analysis for biologists (MATLAB)
Second (Weeks 5–8)	Metabolic Cost of Running Biomaterial Properties Fluid Dynamics Flight Forces	Team presentations Class feedback session Advice on scientific presentation Literature searching in biosciences library
Third (Weeks 8–12)	Field Biomechanics Dynamic Modeling Adhesion (Geckos) Visualization of Flight Airflow	Team presentations Class feedback session Writing a scientific publication Brain-storming and generation of proposals
Independent projects (Weeks 12–15)	Experimental Design; Initial Measurements Final Measurements and Analysis Team Presentation and Final Paper	Project exploration Consultation; definition of hypotheses

using 3D musculo-skeletal dynamic models (see Supplementary Material for all laboratory handouts). We provide students with a Worksheet and Spreadsheet for each laboratory. The Worksheet guides the teams' weekly laboratory reports. We do not have students rehash an Introduction or Methods. Worksheets suggest approaches to Results (analysis and interpretation of data), and ask students to propose next-step, novel experiments (see Supplementary Material). We also require each team to share their data in a Spreadsheet. Each week teams are only able to attain a small sample size for each laboratory experiment. By sharing data from all four teams in a rotation, the team that presents the results in the symposium at the end of the rotation has sufficient data to make more general conclusions. The sharing of data develops a sense of community among all students in the class.

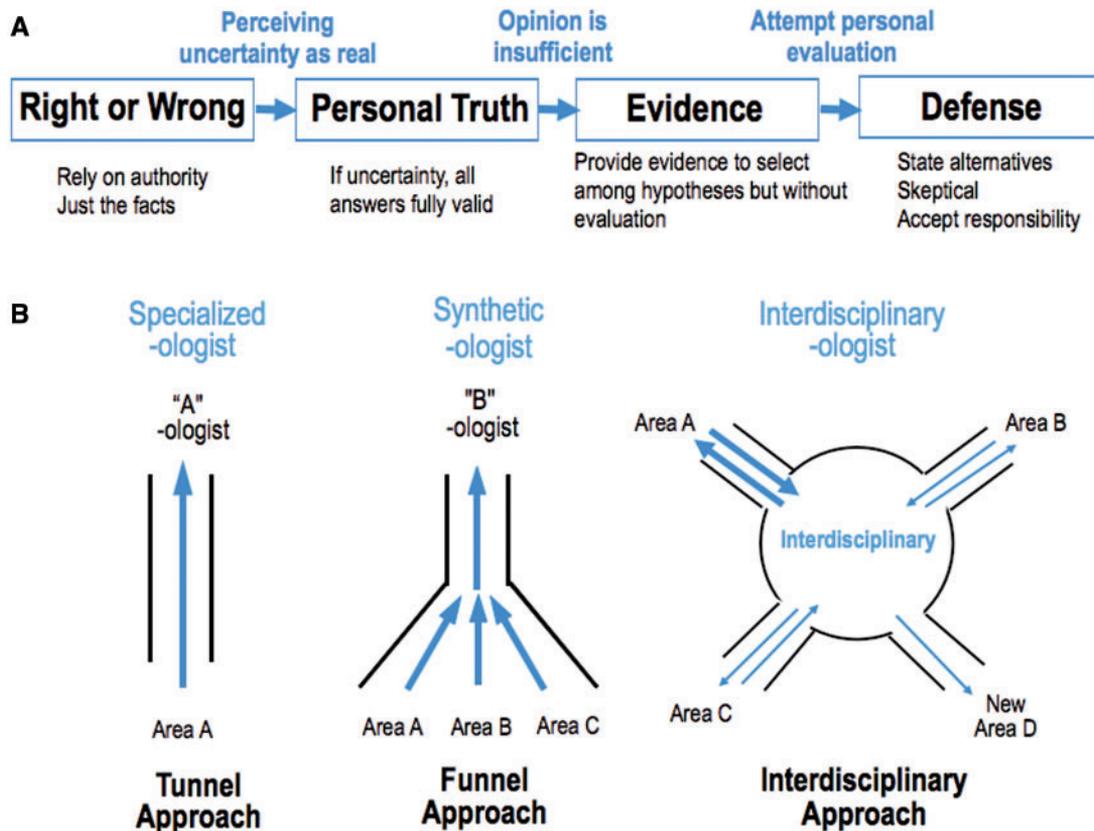
### Discussion section

To complement the laboratory and provide students with the tools necessary for interdisciplinary discovery, we offer a 1-h discussion section each week for the whole class. Discussion sections deliver advice on various aspects of the scientific process, serve as a forum for students' feedback, and give students an opportunity to present their findings (Table 1). We provide tutorials on organismal diversity for engineers with the help of biologists, and on collection and analysis of data (MATLAB) for biologists with assistance from engineers. In discussing experimental design, we focus on the selection of parameters and variables, testable hypotheses, sample sizes, control groups, measurements of outcome, accounting for variability, statistics, and the scope of inference of findings consistent with rubrics for assessment of

experimental design (Dasgupta et al. 2014). We set up a session with library experts to show how to conduct comprehensive searches. We provide advice on scientific writing, grant proposals, and presentations at professional meetings. Students have the opportunity to provide constructive criticism openly on each rotation. Each mentor uses a rubric for presentations by the team that provide feedback to each group (see Supplementary Materials for presentation rubric).

### Independent projects

The final 3 weeks of the semester is devoted to independent projects for which teams are required to make an original discovery. Initially, students submit one-page proposals based on their interests, curiosity, literature review, and the research stations used during the rotations and available for further work. We encourage students to seek teammates so as to form groups of three to five students interested in a particular question. We did not dictate the composition of the teams. During discussion, students brain-storm collectively and begin to generate novel hypotheses that they start to formalize. The proposed project must be original, as judged by an exhaustive review of the literature and the extensive knowledge of the faculty and graduate student assistants. During the second week, students explore their hypotheses and make initial measurements in CiBER during class and arranged times. By the beginning of the third week, students have revised their hypotheses and have made the final measurements. They present their final projects by writing a team paper and giving a team presentation to the class in a culminating symposium. Final projects often lack sufficient replicates for publication, given the short time



**Fig. 3** Trajectories for development. (A) Stages in a model of critical thinking (after Perry 1970). Structure of the laboratory facilitates transition from right-or-wrong thinking, found in “cookbook” laboratories, to stages by introducing intentional uncertainty so that students must consider evidence that results in a position they defend personally (moving from left to right). (B) Approaches to learning. Students have been trained to be discipline specialists (“tunnel” approach) with more or less synthesis of other areas (funnel approach). By intentionally composing teams containing both biologists and engineers, we encourage a specialist (Area A) to learn how to benefit from (arrows from Areas B and C) and contribute to (arrows toward Areas B and C) the interdisciplinary team. (This figure is available in black and white in print and in color at *Integrative and Comparative Biology* online.)

available. We offer teams the opportunity to complete their study during the summer, to present their findings at a national meeting, and to publish their discovery in a journal of high quality.

### Developing critical thinking to facilitate original discovery

Our discovery-based laboratory is highly structured, but is not “cookbook.” Random groups of students do not conduct the identical exercise with duplicated equipment, and with an expected “right” answer. Each week, our teams have two 3-h laboratory periods at a given research station. After they become familiar with the equipment and procedures, they are given a research challenge that appears to have an obvious “cookbook-like” outcome on information given in lectures and readings. We try to intentionally design the laboratory so that their results do not meet initial expectations, often because they must consider additional parameters. In the second laboratory period using the same station, the team must

design their own simple experiment to explain more of the data. Often these experiments represent novel contributions to research that, if followed up, can be published.

This progression in critical thinking parallels the models of Perry (1970) and their further developed variations (Nelson 1989; Baxter Magolda 1992; King and Kitchener 1994; Felder and Brent 2004; Fig. 3A). Students initially consider information in terms of right and wrong, relying on authority to deliver the truth. Realizing that uncertainty is inevitable, they develop their own personal truth that seems intrinsically valid. Since other investigators also found different results, students feel that they have a right to their own opinion, just as others do. Realizing then that opinion alone is insufficient, students begin to provide evidence for different hypotheses. Finally, realizing that personal evaluation is needed to develop a defensible, evidenced hypothesis, they begin to state alternatives, are skeptical of unsupported statements, and accept responsibility for their positions. Students

must present and defend results for one experiment in each rotation, and for their final independent project. The remarkable transformation of a student who expects to find facts given by authorities to a more independent, skeptical, and critical thinker can occur in a single semester.

The guided inquiry by direct questioning (Weaver et al. 2008) we use for the 6 hrs of laboratory each week gives us an opportunity to engage each student deeply in scientific thinking. We pose questions to students involving choice of organism, responsible use of animals, approach to measurement, generation and testing of hypotheses, operational definitions, controls, individual variation, sample sizes, repeated measures, statistical models, graphical representations of data, interdisciplinary collaboration, the publication process and its strategies, and defining a benchmark discovery, not to mention issues of grant support, safety, and ethics. By using the rotations, students are guided by different mentors each week who take a diversity of valuable approaches. One mentor may emphasize critical thinking in discovery, while another leads students through experimental design or excites them by sharing their research experiences. In sum, we attempt to realize the knowledge integration encouraged by Linn et al. (2015) that includes developing practices, expanding content knowledge, understanding the nature of science, and encouraging students to develop an identity in science by eliciting, adding to, and distinguishing ideas. Our overarching goals include having students experience the value of a true understanding of falsifiability, the logical foundations of scientific arguments, comprehensiveness, honesty, replicability, and sufficiency (Lett 1990). Students emerge from our course immersed in these principles, and are 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, regarding students as researchers and faculty members as mentors of research moves the students along a path of personal discovery, realizing concepts new to themselves, and ultimately experiencing the excitement of original or universal discovery in their independent project (Elsen et al. 2009).

### **Mutualistic teaming—realizing the value of interdisciplinary approaches**

Interdisciplinary approaches are required for transformative research (NAS 2004; NRC 2010, 2014; AAAS 2013). Increasingly, collaborations among

disciplines are necessary to be on the cutting-edge of scientific discovery. Disciplinary boundaries are disappearing as disciplines are being integrated at an unprecedented pace. Therefore, training future scientists, engineers, and educators must be explicitly interdisciplinary. One goal of our course-based research laboratory is to have students realize the value of interdisciplinary approaches directly in the processes of collecting and analyzing data, writing their laboratory reports, forming their teams, and conducting experiments for the final, original research projects.

We see at least three approaches to training that we characterize by their extent of integration (Fig. 3B). Most common among our students is the “tunnel” approach which results in a student who is a specialist with deep knowledge in a single discipline, but no knowledge of other disciplines, nor the ability to communicate effectively with scientists in those disciplines. A smaller, but growing group of students take a “funnel” approach which necessarily integrates the knowledge of several disciplines, resulting in a more synthetic specialist with a broader vision, but still lacking the skills to effectively collaborate across disciplines. The third approach, which we term interdisciplinary, requires that a student attain deep knowledge in a specific field, but explicitly is also trained to contribute to, and benefit from, other fields. This approach results in interdisciplinary scientists with the highest probability of creating a new field. Our group’s most effective collaborations in scientific research move beyond altruistic teaming whereby one sacrifices disciplinary discovery to solve a common problem. Instead, we make sure that discoveries in one discipline necessarily lead to advances in a collaborator’s field. In turn, their disciplinary discoveries further advance our own field. The collective discoveries that emerge from this mutualistic teaming are beyond what any single discipline could do and begins to approach the notion of “convergence” (AAAS 2013; NRC 2014). Engagement remains high because the collaboration solves the common problem by directly benefiting one’s own discipline.

The structure of our course-based research laboratory facilitates students moving toward an interdisciplinary approach to research in science. In every laboratory session, students gain respect for the skills and disciplinary knowledge of their peers. Students realize that is not possible to be an expert in all disciplines. In designing their novel experiments in the second of our 3-h laboratory sessions each week and during the independent projects, students learn explicitly how to give to, and benefit

from, the other disciplines. Most realize, especially when given the 3-week constraint on time, that a novel discovery during independent projects requires the integration of knowledge from biologists about the organism and experimental design with the data collection and quantitative skills that engineers bring. Biology and engineering students experience first-hand that collaboration by mutualistic teaming allows them to achieve discoveries beyond that of their own discipline.

### **Instruments and methodologies of assessment**

We use a variety of instruments and methodologies to assess the impact of the discovery-based laboratory on students' learning and on the success of teaching. These include direct oral feedback in laboratories when using the Socratic-style method in teams, direct oral feedback in discussion sessions involving the whole class, scientific writing with guided laboratory reports, team presentations using a rubric, and original discovery in final projects. More recently, we began to develop and conduct surveys and interviews focusing primarily on development of the interdisciplinary skills of critical thinking, communication, and collaboration.

### **Progression of epistemological and intellectual growth**

Because of our considerable investment in instructors, our layered approach to mentoring and our unique rotation system, each mentor was able to assess each student through direct oral feedback in laboratories by using a Socratic-style method. Through questioning about background knowledge, experimental design and analysis, and interpretation of results, mentors were able to assess generally where each student was in their development of critical thinking and ability to make an original discovery.

### **Students' evaluation and reflection**

Especially in the early years of the course, we benefited significantly from direct oral feedback in discussion sessions that included the whole class. Students would evaluate the previous rotation by openly commenting on which laboratory experiences were most beneficial, which required revision, and what possibly might be added to the course.

### **Scientific writing with guided laboratory reports**

Graduate Student Instructors read and graded the guided laboratory reports each week. Their

comments address not only scientific writing, but also specific errors and misconceptions in data analysis, statistics, and interpretation of results. In addition, Graduate Student Instructors encourage students to think about the next experimental step, as required by our Worksheet, moving them toward possible final projects.

### **Team presentations using a rubric**

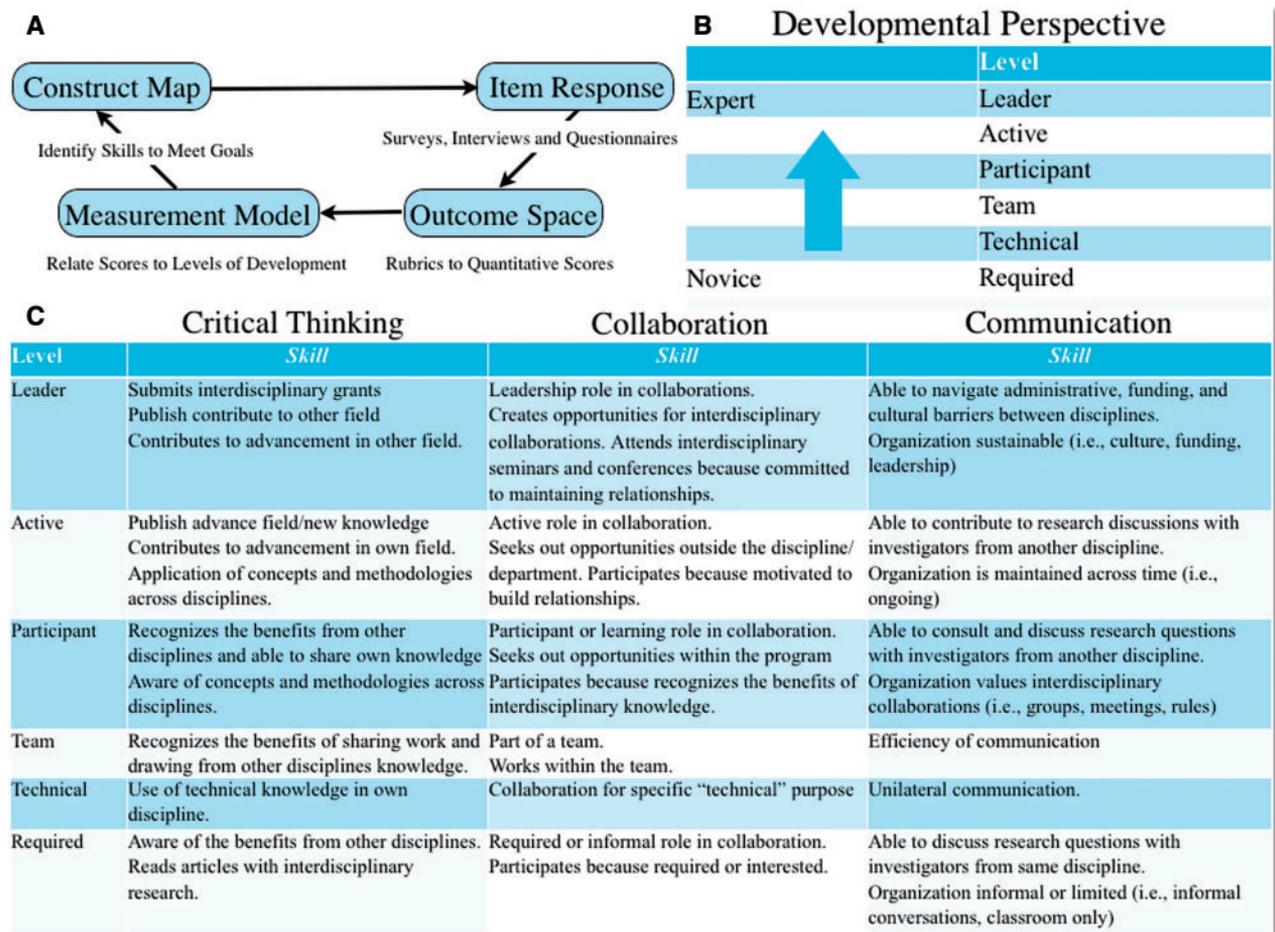
Teams select one experiment from two of three rotations and their final project to present to the whole class in the symposium (Fig. 2). Each student in the team delivers one section of a 20-min presentation, so teams were required to collaborate, communicate, and choreograph their talks. During the discussion section on advice about their presentations (Table 1), we provide students with a rubric to guide their presentations (see Supplementary Material). Each mentor uses the rubric to score each presentation. These are summarized for the students along with additional comments providing feedback for their presentations.

### **Products of original discovery from the final project**

As our most direct measure of gains in course-based research, we attempt to track students' presentations, abstracts, and final publication. At present, six publications have appeared in journals with four more in preparation. In addition, at least 16 abstracts have been published and presented at national meetings. Several independent projects became parts of students' PhD theses (Gillies et al. 2014). Another project, that ignited a new field of inertial appendage control in biology and robotic engineering, appeared on the cover of journal, *Nature* (Libby et al. 2012).

### **Development of assessment tools**

The foundation of our assessment tools was the BEAR Assessment System (BAS) developed by Wilson (2005, 2009). The BAS is an approach to the development of assessment that guides and supports the design and validation of assessment tools through four building blocks (Fig. 4A). The first building block was to create a multidimensional construct map for IDR. A construct map concretely identifies variables, described as capabilities, approaches, attitudes, and skills that can be observed to assess whether students are meeting goals. We assigned six levels of development or success to a given construct—from Novice to Expert (Fig. 4B). We specified the data necessary to demonstrate each level of success with three main variables that



**Fig. 4** Approaches to assessment. (A) Assessment using the BEAR Assessment System (BAS) (Wilson 2005). Development of tools for assessment is a dynamic process of continual revision of construct map, item response, outcome space, and measurement model. (B) Attempts to characterize stages in the development of an interdisciplinarity perspective. (C) Construct maps for assessing students' skill in critical thinking, collaboration, and communication. (This figure is available in black and white in print and in color at *Integrative and Comparative Biology* online.)

included: critical thinking, collaboration, and communication (Fig. 4C).

Once we designed our multi-dimensional construct map, we then created the second building block, namely an item response or observation in the form of surveys, interviews, and questionnaires (Fig. 4A) directly aligned to the construct map (see Supplementary Material for survey questions; Supplementary Fig. S1). For the third building block, we generated a scoring guide or "outcome space". These are rubrics that translate the response of our surveys, interviews, and questionnaires into quantitative data or scores. Our fourth building block consisted of developing a measurement or interpretational model to relate the scores of the surveys and interviews (items) to the levels of development in our construct map. We analyzed the responses to the survey items with item response theory (IRT) and the notes on interviews by using

content analysis guided by the construct map (Hambleton et al. 1991). We want to emphasize that this process of assessment is an iterative one. Each time a survey or interview was given and progress assessed, we went back and revised our construct. We approached our constructs as hypotheses that reflected progress. Each round of assessment tests these hypotheses. This scientific approach to assessment resulted in an effective final instrument of assessment that we suggest can be used more generally for assessing progress in IDR.

We view the success of our assessment thus far as the construction of an effective tool, not as definitive evidence of growth in interdisciplinarity. Our preliminary survey of students before and after the course provided empirical evidence that students developed interdisciplinary skills. An IRT rating-scale model applied to the survey data gave statistical evidence that the assessment was reliable and that the steps in the

scale of response (e.g., agree strongly to agree) were ordered (Andrich 1978; Wright and Masters 1982). IRT models place the difficulty of responding to each item and the ability of students described by the construct on the same scale (Supplementary Fig. S2). Comparing the pre-survey and post-survey responses showing the students' ability distributions indicated that more items are needed to assess the higher end of the distribution (see Supplementary Materials for analysis). Analysis of the content from interviews with students provided evidence of common ways in which individuals were developing interdisciplinary skills, but on different trajectories (Supplementary Fig. S3).

### Challenges to implementation

Many challenges exist regarding the implementation of interdisciplinary, course-based experiences in research. Perhaps, foremost among these, is the fact that we have insufficient assessment to actually know what students gain from course-based experiences in authentic research and how we should shape them. Linn et al. (2015) noted that, "Fewer than 10% of the studies validate self-reports with analysis of research products (such as presentations or culminating reports), direct measures of content gains, longitudinal evidence of persistence, or observations of student activities." Moreover, many of the institutional barriers detailed in the NAS Report on Facilitating IDR (2004) still remain.

Resources for course-based, authentic research vary significantly among institutions. We believe that the core principles of our learning laboratory can be exported, adapted, and matched to local environments. Besides using research equipment from a center (CiBER) as we did, equipment already in teaching laboratories, shared departmental equipment, and investigators' own laboratory equipment can all be sources for successful experiences in authentic research as they have at a variety of institutions (Kloser et al. 2011; Wei and Woodin 2011; Brownell et al. 2012). Low-cost equipment and techniques can be used for many discovery-based exercises. For example, Ryerson and Schwenk (2012) designed an inexpensive digital particle image velocimetry system. Wind tunnels can be built from cardboard and window fans, measurements of the flow of water in the field can be achieved by video-recording or timing particles carried in a stream, and material properties can be measured by hanging weights onto specimens. Examples of inexpensive techniques for teaching biomechanics are described by Vincent (1978). See the journals *Advances*

*in Physiology Education* and *American Biology Teacher* along with the SICB Digital Library (<http://www.sicb.org/dl/biomechanics.php3>) for many simple, inexpensive experiments on the jumping of locusts (Scott 2005), the running of spiders (Bowlin et al. 2014), the swimming of leeches (Ellerby 2009), and the elasticity of bone (Fish 1993) that can be modified to fit a discovery-based approach. Another strategy is to use far fewer diverse laboratories employing a more limited number of techniques as modeled by the Science Education Alliance Phage Hunting Advancing Genomics and Evolutionary Science program which takes advantage of the diversity of the bacteriophage population to engage students in discovery of new viruses, the annotation of genomes, and comparative genomics, using common equipment for all teams (Jordan et al. 2014).

The time that faculty, students, and staff devote to mentoring can be limiting. Fortunately, restructuring early undergraduate discovery-based course experiences has shown success in scaling-up to larger classes. The Freshman Research Initiative at UT Austin serves more than 750 freshmen each year who participate in a year-long, potentially publishable research project (<https://cns.utexas.edu/fri>). Rather than integrating parts of research into traditional laboratory courses, the initiative revolves around a "Research Stream," a fully functional research laboratory in which students do cutting-edge research supplemented by weekly lectures that are organized around the work being carried out in the laboratory. Each Research Stream is led by a faculty member who provides guidance, set goals and directions, and develops and teaches a research-experience course to the students only within their stream. Research laboratories themselves are each run by a "Research Educator", a PhD research scientist dedicated to each Research Stream. In engineering, the "Vertically Integrated Projects (VIP) Program" at the Georgia Institute of Technology involves more than 300 undergraduates with nearly 30 VIP teams (Coyle et al. 2014). Multidisciplinary teams participate in the course for up to 3 years on original projects designed by faculty and mentioned by senior undergraduates.

Our model for developing critical thinking by challenging students each week with unexpected findings, selecting diverse teams to facilitate interdisciplinary collaboration, and building practical skills in our discussion section, offered in parallel with experiments, can be adopted individually to best match particular objectives of the course. We would be glad to assist interested groups in attempting to implement any portion of the structure of our

interdisciplinary, course-based research experience here at Berkeley.

## Acknowledgments

The authors thank Kellar Autumn who was an original pioneer of an earlier version of this approach in physiological ecology. They also thank their engineering colleague, Ron Fearing, for assisting in the adhesion laboratory, but more importantly for encouraging students in engineering to take their course. In particular, they thank Simon Sponberg and Eve Robinson as well as all the Graduate Student Instructors who contributed to the course over the years—Evan Chang-Siu, Jean Mongeau, Dennis Evangelista, Ardian Jusufi, Yu Zeng, Kaushik Jayaram, Marc Badger, Erin Brandt, and Duncan Haldane. Thanks go to Pauline Jennings for managing the IGERT and more. They thank John Matsui, Mary Full, and C.F. Herreid for improving the manuscript. Finally, they thank all the students who dedicated their time and effort to make the course a success.

## Funding

This work was supported by the University of California at Berkeley to RJF for starting CiBER and a National Science Foundation Integrative Graduate Education and Research Traineeship Grant [IGERT, DGE-0903711 to R.J.F., M.A.R.K., R.D., and Ron Fearing]. The presentation in the symposium at the Society for Integrative and Comparative Biology was supported by a grant from the US Army Research Office to L. Waldrop [W911NF-14-1-0326]; by the Society for Integrative and Comparative Biology (Divisions of Animal Behavior, Comparative Physiology & Biochemistry, Comparative Biomechanics, and Vertebrate Morphology).

## Supplementary data

Supplementary data available at *ICB* online.

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