Undergraduate research communities: A powerful approach to research training

Scott Kight, Montclair State University

Available at: https://works.bepress.com/scott-kight/10/
During freshman orientation, we ask biology students to raise a hand if they plan to attend medical school. Almost every hand in the room goes up. Regardless of the roots of this phenomenon, the unpleasant truth is that only a handful will gain entrance into a medical program (Hinkley 1997).

The dramatic difference between interest and acceptance into medical schools leaves many science majors scrambling for new career goals during and after senior year. Unfortunately, students often view graduate study as an option of last resort, and as a consequence enter such programs under-motivated, under-prepared, and uninformed about the nature of academe.

Our department took a relatively novel approach to this dilemma. First, we required all undergraduate life science majors to participate in research. Second, we created an elective yearlong course sequence in which students actively engage in the many facets of research in a teaching laboratory setting. This approach differs from traditional student-faculty research in several ways:

- Students design and conduct their own original research projects. Professors foster intellectual development but do not drive it.
- Students work as individuals or in small teams, but routinely discuss their ongoing research with, and provide peer review for, other members of the cohort.
- Students participate in all aspects of original scientific research including concept development, hypothesis construction, literature review, experimental design, proposal writing, data collection, analysis, and written and oral presentation.

Our approach resembles a learning community, in which groups of students learn together in cohort-based environments. The courses require faculty mentoring, but the primary emphasis is on a student-generated research experience. This reflects the nature of graduate and postgraduate research training, and provides undergraduate students an opportunity to critically evaluate their own work and that of others. This approach fosters self-direction and enhances intellectual sophistication by presenting students with unknowns, alternatives, and uncertainties. Students must confront misconceptions about science, learn to critically evaluate existing knowledge, and competently discover new knowledge.

Undergraduate research programs with student-centered components are generally successful (Bartlett 2003; Rehorek 2004). Laboratory courses characterized by guided design and student research improve student comprehension and motivation (Fail 1991), and enhance thinking and problem-solving skills (Basili and Sanford 1991). Successful endeavors have been described for chemistry (Fasching and Erickson 1985), engineering (Posner and
Markstein 1994), genetics (Lewis 1999), behavioral science (Vestal and Estes 1992), wildlife science (Millsap and Millenbach 2004), and environmental science (Sherman and Woy-Hazleton 1988). Our program builds upon this approach by allowing students to develop and execute their own research plans from start to finish.

Research communities and the major curriculum

Montclair State University (MSU) presently enrolls 12,000 undergraduate students, of which 700 major in biology or molecular biology. The Department of Biology and Molecular Biology is home to 19 research-active scientists and includes in its mission the offering of research and writing-intensive experiences in the classroom and laboratory that permit students to gain the intellectual and practical skills to succeed in rewarding careers. Life science majors at MSU come from diverse backgrounds: over 40% are African American or Hispanic and over 60% are women.

We developed our undergraduate research cohort program with support from the National Science Foundation (NSF). With these funds, we purchased high-tech equipment, including an automated DNA sequencer and an infrared gas analysis system, for dedicated use by students in the courses. Because the experience is immersive and relatively long-term, it is important for undergraduates to have reliable access to critical equipment items for their research activities to be successful.

Three two-semester course sequences, in three conceptual areas (molecular biology, organism biology, and ecology), were developed for the biology major curriculum, and they satisfy requirements for a research elective and also an elective in the particular topical area. Although the three versions differ with respect to focus, all follow a similar curricular approach.

From the first day of class, students participate in hands-on activities designed to develop observational skills, increase familiarity with experimental design, aid in searching and critically reading the scientific literature, and help them become comfortable with the idea of being peer-reviewed and constructively evaluating the work of others. For example, on the first day of the organism biology version of the courses, students are presented with an unfamiliar organism to observe. Students work in groups to identify the organism, note interesting behavioral or morphological patterns, and search the internet for information and journal articles about the species. Students formulate hypotheses about patterns they find interesting and have a discussion about ways to experimentally test their hypotheses. Students then design and run experiments, collect and analyze data, and discuss their results with the class. This single activity provides a concise preview of the entire course and lays the foundation for more rigorous activities in future weeks.

As the semester progresses, students discuss biological ideas that they personally find interesting and exhaustively search the scientific literature for relevant studies. Peer evaluation helps students identify additional areas in the literature that may need further examination. Students thereby develop experimental plans that are informed by knowledge of past studies. This process culminates in a written peer-reviewed grant proposal that includes a concise review of the most relevant literature, experimental plans, a research timeline, and a modest budget request.

Solid proposals are modestly funded (from the department supply budget), and each student conducts the proposed experiments in the second semester of the course. Student groups work independently in this phase, but the entire cohort meets regularly to discuss ongoing experiments. Near the end of the second semester, the class learns about statistical analysis and presentation of data. Each student writes a research manuscript following the format of a scientific journal in the particular field of study. During the last week of the semester, students peer-review the manuscripts and give a professional-quality oral presentation to an audience of students and faculty. Most students subsequently present their work at regional scientific meetings, and some prepare manuscripts for publication.

Example I: Research community in molecular biology (BIOL482/483)

Most biology undergraduates have a firm grounding in molecular biology by their junior or senior year, but many lack direct experience in modern molecular techniques such as polymerase chain reaction (PCR) and DNA sequencing. We therefore initially provide students in the molecular biology version with a crash course in molecular techniques, with hands-on experience in critical techniques such as micropipetting, agarose gel electrophoresis, sterile technique, PCR, and DNA sequencing. In one activity, for example, students isolate their own DNA (using a noninvasive saline mouth rinse), amplify part of their mitochondrial DNA (mtDNA) using the PCR, and sequence through this amplified region using Sanger dideoxy chemistry. Students specifically amplify the mtDNA D-loop region, which is polymorphic and affords the opportunity for comparison with other individuals using software tools available on the internet (www.geneticorigins.org/geneticorigins/mito/mitoframeset.htm). Through this activity, students gain an excellent introduction to a set of core techniques widely used in modern laboratories. Also, a few molecular biology majors familiar with these techniques are typically
in the course and serve as mentors for less experienced students. Students are genuinely excited about isolating and sequencing their own DNA, and in one recent cohort this generated substantial interest in mitochondrial genomes, which became the focus for all the groups that year. During the first semester, students researched the scientific literature and presented mini-seminars on mitochondrial morphology, structure, biochemistry, metabolic pathways, genomes, mitochondrial-based genetic disorders, nuclear-mitochondrial interactions, and so on. From these weekly discussions, the four groups (of three or four students each) eventually developed research projects related to mitochondrial molecular biology. Two chose to examine the role of the mitochondrion in programmed cell death, one chose to investigate the telomeres of linear mtDNA, and another looked at changes in nuclear gene expression in yeast cells in the presence and absence of mtDNA. We briefly summarize two of these projects in Figure 1.

Example II: Research community in ecology (BIOL 484/485)

Students in the ecology research community courses spend most of the summer at the New Jersey School of Conservation (NJSOC), located on a 240-acre tract and surrounded by 30,000 acres of state

FIGURE 1

Examples of student projects.

Example One (Molecular Biology). Telomeres of Hydra mtDNA. Although most mitochondrial genomes analyzed to date are circular dsDNA, limited organisms have been identified with linear dsDNA genomes. Students wondered how the ends (telomeres) are replicated and organized in these organellar genomes. The role and structure of telomeres in eukaryotic chromosomes is well studied, but little is known about linear mtDNA telomeres. The group chose to study the Cnidarian Hydra littoralis, which was the first species identified with a linear mtDNA genome. Students cultured hydras, developed protocols for the isolation of mitochondria, and purified hydra mtDNA. They also developed PCR primers (based on limited hydra mtDNA sequence data available in GenBank), amplified regions of the hydra mtDNA near the telomeres and performed DNA sequence analysis of the PCR products. They also collaborated with a student from another course (Scanning Electron Microscopy) to visualize the linear mtDNA molecules by electron microscopy. They presented their work at a local scientific meeting, and one student subsequently entered our graduate program and continued the work as an MS thesis.

Example Two (Molecular Biology). Nuclear-Organellar Communication: Altered Nuclear Gene Expression Profiles in a Yeast Mitochondrial DNA Mutant. Another group was curious about the interaction between mitochondrial and nuclear genomes. Mitochondrial biogenesis requires cooperation of both nuclear and organellar genomes. Many important mitochondrial proteins (e.g., F1 ATPase and rproteins) are heterologous, requiring subunits encoded by both nuclear and mtDNA. To investigate this cooperation, students used yeast DNA microarrays, provided (at little or no cost) by the Genome Consortium for Active Teaching (GCAT) (www.bio.davidson.edu/projects/GCAT/gcat.html). The yeast chips were manufactured by the Institute for Systems Biology (Seattle, WA) and included all known genes from the yeast nuclear genome printed in multiple copies in this array. By isolating total RNA from yeast cells, they used these microarray chips to interrogate changes in the transcriptome of Saccharomyces cerevisiae in the presence (wild type DL-1) and absence of mtDNA (DL-1 rho0). The wild type and rho0 mutant had identical nuclear backgrounds, although the rho0 mutant had a petite phenotype due to the absence of functional mitochondria. They found that genes involved in mitochondrial and cell wall biogenesis, cellular stress responses, and glycolysis were induced in the petite mutants. Likewise, ATP-binding cassette transport proteins were also induced. In contrast, genes involved in the assembly of the F0-F1 ATP synthase as well as genes involved in aerobic respiration were repressed in the petite mutant. Their findings support previous reports of a retrograde response in yeast, involving the adaptation of nuclear gene expression levels at times of mitochondrial dysfunction, and have implications for the role mitochondria in apoptosis, cellular aging, and response to stress. They presented their work at several scientific conferences. Their results were subsequently replicated by another research group, and are in preparation for submission to a scientific journal.

Example Three (Ecology). Navigation via Putative Magnetoreception in Eastern Red-Spotted Newts. During his literature review, one student became interested in magnetic compass orientation in newts. Other studies examined this phenomenon in controlled laboratory conditions, but the student found few references to field-based experiments. He collected newts from shoreline habitats and observed them in circular arenas at four different locations relative to the collection site. Experiments were conducted in both midmorning and midafternoon to control for celestial cues. Newts were significantly more likely to occupy the arena quadrant facing the collection site. He discussed the adaptive significance of navigation at a regional scientific meeting and is presently preparing his results for journal submission.

Example Four (Ecology). Melanism and Shade Preference in Eastern Red-Spotted Newts. Students observed variation in melanism among newts and other animals. One team predicted that this variation was associated with microhabitat differences in shade, and that newts from shaded areas would be darker than those from unshaded habitats. They further predicted that newts would exhibit light/dark behavioral preference associated with their natural habitat. Students mapped shaded areas of the lake during midmorning, noon, and midafternoon. Newts were collected from areas either exposed to sunlight or shaded at all three times. Students observed newts for 15 minutes in a circular arena with one half shaded by an opaque cover. Halfway through the observation period, the cover was moved to the opposite arena side to control for positional bias. Animals were then photographed and the luminosity of images analyzed digitally. Both larval and adult newts collected in shaded habitats were significantly darker than those from unshaded habitats. However, both groups significantly preferred the shaded half of the arena. Students presented at a regional meeting and are preparing a manuscript for journal submission.
forest and federal lands. It is one of the largest undeveloped tracts in New Jersey, and an ideal setting for field-based research activities.

The ecology sequence is an accelerated eight-week experience (two four-week summer session courses). The NJSOC provides room and board, and the class spends at least one overnight each week, permitting a very immersive experience. Students learn to use global positioning system technology to map spatial patterns, as well as quantitative and qualitative sampling methods to characterize the fauna and flora of the surrounding deciduous forest and two on-site lakes. As with all versions of the research community courses, students learn to conduct comprehensive reviews of the scientific literature, design solid experimental plans, perform statistical analyses, and write peer-reviewed research proposals and manuscripts.

Some specific examples of student-designed ecology research projects include antipredator mechanisms, magnetoreception, and microhabitat behavioral variation in Eastern red-spotted newts (Notophthalmus viridescens); reproductive ecology of bluegill sunfish (Lepomis macrochirus); adaptive morphology and sexual cannibalism in fishing spiders (Dolomedes triton); adaptive physiology of stonefly larvae (Plecoptera); mineral uptake and antimicrobial activity in bryophytes; and allelopathic properties of soil in Eastern hemlock (Tsuga canadensis) stands. We describe two projects involving red-spotted newts in Figure 1.

Conclusion

Undergraduate research learning communities are an immersive and comprehensive approach to research training. An external

FIGURE 2

Guidelines for student proposals.

To provide a conceptual framework and illustrate the various components of a research proposal, we provide and discuss with students the grant proposal guidelines published by the NSF. However, because the NSF guidelines can be overwhelming, we also provide students with sample proposals from previous semesters, and also course-specific guidelines. An example of these guidelines follows.

RESEARCH PROPOSAL GUIDELINES

Research Community in Ecology

I. Introduction and Background. This section should resemble your previously submitted literature review, but will differ in the following ways:
   • There is no need to include references that are clearly not relevant to your proposed project.
   • There is a need to include references that support the general background of your proposed idea—including related studies on entirely different organisms.
   • Describe also the particular study site, the history of the lakes, and so on.

II. Research Objectives and Hypotheses. This section should be a general discussion of what exactly you intend to study. What is your general question, and why is it worth asking? What do you predict is going to happen? Why do you predict it? What other alternatives (including the null hypothesis) are possible? How are your objectives related to the literature you reviewed?

III. Materials and Methods: This section describes exactly what you intend to do. You may have one big experiment, but more than likely you will have a series of related experiments designed to account for several variables that cannot be controlled with a single experiment. Include the following general kinds of information:
   • What question(s) will be answered by the experiment(s)?
   • When will the study take place (and for how long)?
   • How often will measurements be taken?
   • What exactly is going to be measured? (This can [and should] be multiple things.)
   • How will you go about taking these measurements? (You need to be systematic.)
   • How will you ensure your measurements are objective and not biased?
   • How will these measurements address your question(s)?
   • Describe any special materials: enclosures, containers, recording devices, and so on.
   • How many people are needed to run the experiment(s)?
   • What are the limitations of your design? (Are there factors not controlled?)
   • How will you attempt to overcome these limitations?
   • What are all the alternative outcomes of each experiment?
   • What would you conclude from each alternative?

This section should read very much like a Methods section in a scientific journal article. Read the Methods sections carefully in the literature you reviewed, and use these as guidelines for writing your own. Yours, however, will most likely be much more detailed and include things that a standard Methods section does not include.
program evaluator reported that most students felt their expectations were met or exceeded, and in particular found value in the opportunity to design and conduct their own research projects. More than 80% of program students who graduated from college between 2001–2003 ($N=16$) were in MS, PhD, and professional programs, or had entered a research career by 2004. This placement rate is far higher than in the general pool of biology majors at Montclair State University, which have a 40–50% placement rate estimated from senior-year tracking and post-baccalaureate reporting.

We should note particular logistic and staffing issues associated with our approach. For example, the courses occupy a significant portion (in our case 40%) of the instructor’s annual teaching load. The instructor is therefore unavailable to staff several other course sections in the major—courses that generally have higher enrollments. Also, scheduling the ecology version of the sequence involves a trade-off between the constraints of summer coursework (rapid and compact scheduling; some students unable to attend summer sessions) and the diversity of ecological questions that can be addressed in the summer months. This academic year, we are providing an alternative approach by offering the ecology sequence during the regular academic year with a two-week stay at a tropical field station during the winter break. This approach, however, is accompanied by financial constraints of travel and boarding costs.

**FIGURE 3**

Guidelines for peer evaluation.

Each student evaluates the work of at least four peers in the class. Evaluation is anonymous, and reviewers identify themselves by a numeric code known only to the instructor. Peer-review occurs at several stages in the process: first with a literature review, next with an experimental proposal, and last with the final manuscript. We provide an example of the evaluation sheet that students follow in peer-reviewing the experimental plan (excluding the literature review, which was evaluated previously). After peer-review, authors revise the document and submit for a second round of review.

STAPLE THIS FORM TO THE FRONT OF THE DOCUMENT

Research plan draft

Reviewer identification number _____________________________

Author _________________________________________________

Your mission is to help your peers produce the highest quality research plan possible. This means that your criticisms and comments should be honest, but also constructive.

Please make extensive comments on the document itself. Summarize your evaluation by addressing the following questions:

1. Did the author provide a specific and detailed description of the research plan? If not, please comment on the sections in need of more detail.

2. Were the research hypotheses clearly defined? If not, what must be clarified?

3. Were the independent variables described well? Was it clear how they would be incorporated into the experimental design? If not, what must be clarified?

4. Were the dependent variables described well? Did the author address issues of sensitivity, validity, reliability, and practicality? If not, what must be clarified?

5. Did the author discuss the treatment of nuisance variables? Can you think of any the author forgot that might turn out to be important?

6. Did the author provide a timetable? Can the experiments, as described, be completed within the time limits of the course?

7. Did the author address issues of sample size?

8. Did the author clearly state what materials are needed (and which are already on hand)? Is this list inclusive, or are there other items that must be acquired? Did the budget seem realistic?

9. Comment on grammar in the document. What needs improvement?

10. Comment on readability of the document. Did you need to reread things several times to understand what the author was conveying? What must be improved?

11. Please provide additional comments that you feel will help the author improve the experimental plans described in the document.
Student-driven undergraduate research is not without its challenges. Issues of student initiative, responsibility, and expectations for traditional structure can be impediments. We have found, however, that such issues are generally minimal, and that students hold sophisticated expectations of themselves and their professors. For example, the evaluator reported that most students felt that choice of research project was a feature that should never change. Some students felt that individual research activities should start earlier in the sequence, and should extend beyond the two semesters. Students were also aware of realistic limitations, citing the need for more extensive research facilities, software, and journals (coincidentally among the most common complaints of faculty members!). There was an interesting mix of opinion on who should take the courses: Some participants felt that admission should be selective, while others felt that all biology majors should take the course to learn what it “really means to be a scientist.”

The evaluator described a particularly compelling anecdote from a student who subsequently interviewed for a summer research program at another institution. The evaluator states that following the interview the student reported that she was very disappointed by the description of the extramural program, which involved rotations through several labs to see what they do. When she told the interviewer what she did in the research community sequence at MSU, she said the interviewer was quite impressed and told her that she could not do anything like that in that institution’s summer program. It was at this point that the student reported realizing what a great opportunity she had by participating in the research community program.

The research community courses are clearly valuable to students. Although they obtain course credits, these are pale rewards in comparison to the level of research competence and experience gained. Interest is long lasting—graduates from previous years sometimes visit to see what projects are under development, and share their overall experiences with students presently engaged in the process. The courses were a powerful addition to our curricular efforts, and we welcome inquiry and discussion with faculty at other institutions who may consider adopting a similar approach.

Acknowledgments

This program was developed with a Course Curriculum and Laboratory Improvement grant from the National Science Foundation (DUE # 9980669).

References


