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Bringing the Scientific Process into the Undergraduate Classroom

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In recent years, there has been a call to modernize teaching methods at the college level. Consequently, science courses are becoming more interactive, and undergraduate students are getting more exposure to authentic research (Auchincloss et al. 2014, Brownell and Kloser 2015). Instructors have taken many approaches to increase undergraduate engagement in the classroom, largely through active learning (e.g., flipped classrooms), yet much remains to be learned about how to optimize the undergraduate student experience.

We developed an undergraduate course in the Entomology and Nematology Department at the University of Florida in which undergraduate students actively learned about the scientific process, conducted authentic research, and co-authored a peer-reviewed scientific paper. An overarching goal was to engage underrepresented minorities from a diverse range of majors in basic and applied research. Throughout the course, we emphasized how applied research is intended to advance our scientific understanding of ecological and evolutionary processes and to benefit local and global economies (e.g., breakthroughs in pest management). To achieve these goals, we developed a course structure that engaged students in the entire scientific process. This article describes the course's structure and student learning outcomes in the hope that it might benefit other instructors seeking to engage students with authentic research.

Using a Course-based Undergraduate Research Experience (CURE) model (Lopatto 2004, 2008), 10 undergraduate students participated in two research projects. Graded coursework was integrated with new original research into a unique classroom experience. Students learned by working through the steps of the scientific process, from formulating research questions to collecting and analyzing data and writing a manuscript, all in a classroom setting (Fig. 1). Throughout the semester, students co-wrote a manuscript using previously collected data associated with the evolutionary and ecological function of sperm storage in *Narnia femorata* (Hemiptera: Coreidae; Fig. 1, left image), which was later published in *Annals of the Entomological Society of America* (Allen et al. 2018). We also collaborated with the students to ask novel research questions about a second project focused on two invasive *Neoscapteriscus* species (Orthoptera: Gryllotalpidae), which have been agricultural pests for more than 80 years in the southeastern U.S. (Mhina et al. 2016). Using this second study system, we investigated associations between an introduced parasitic nematode, *Steinernema scapterisci* (Rhabditida: Steinernematidae), and invasive mole cricket morphology, also resulting in a publication (Allen et al. 2020).

Research as the Backbone of a Course

During the first three weeks of the course, we established the pillars of the course's research agenda. For more detail, see the syllabus in supplemental material.

Week 1.

Goals

a. Understand the steps of the scientific method and learn the importance of basic and applied entomological research.
b. Learn the basic biology of the focal organism (*Narnia femorata*) in Research Project 1 and how further research could contribute to science and society.
c. Take ownership of the research by developing hypotheses and experiments.

Activities

a. Through readings, lectures, and discussion, explore the function of long-term sperm storage in insects and its relationship with sexual selection, ecology, and evolution. We guided students to think about the consequences of sperm storage on the insect's mating system.
b. Design an experiment to test the presence and function of long-term sperm storage in our focal organism, *N. femorata*.

Research Output. As a class, we designed the Research Project 1 experiment ("sperm storage in a true bug") and came up with predictions to go with our hypotheses (Fig. 1, middle image). After students demonstrated an understanding of the steps we had covered (through group discussions and presentations), we explained that the experiment had already been conducted in a similar manner as discussed in class. We explained to the students that we, as a research team, would use the previously collected data to write a manuscript during the semester with the goal of publishing it in a peer-reviewed journal (Allen et al. 2018).

Week 2.

Goals

a. Gain understanding of how to read and interpret primary scientific literature.
b. Learn about Research Project 2, focused on invasive mole crickets.
c. Learn how to use ImageJ (imagej.nih.gov/ij/) to collect morphometric data.
d. Learn about the value of the Open Science Framework (OSF.io) for collaborative research. This online platform was used to distribute, measure, and submit mole cricket images and their measurements (Excel sheets). Links to software downloads (e.g., ImageJ), external platforms (e.g., OSF), and course content were provided via an online learning platform (e.g., Canvas).

Activities

a. Search for primary scientific papers relevant to both research projects.

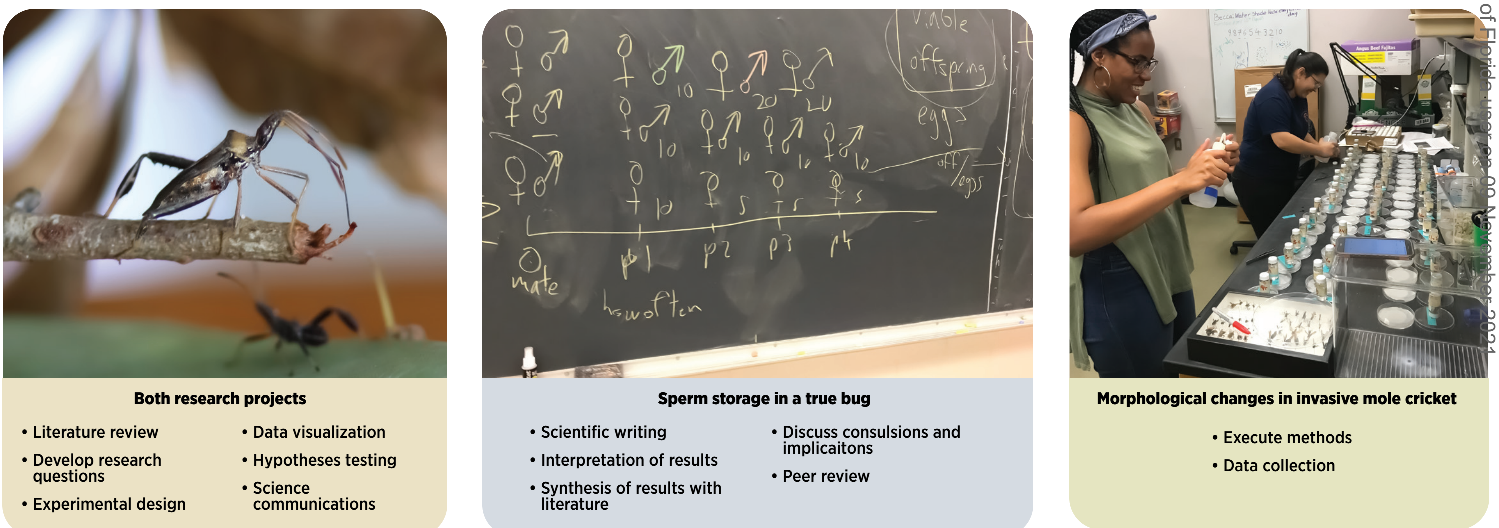

Fig. 1. Framework of the course, outlining the components of the scientific process that were discussed and performed for each research project: the "sperm storage in a true bug" project, for which we used previously collected data, and the new "morphological changes in invasive mole crickets" project. From left to right: Hemiptera (Coreidae), study organism (photo by CWM); classroom exercise on the experimental design used in the sperm storage study (photo by PEA); and undergraduate researchers preparing mole crickets for parasitic nematode extraction (photo by PEA).

b. Review the history of invasive mole crickets in the U.S. Southeast and classical biological control (BC) efforts over the past four decades. Introduce several remaining questions about the recent ecology of the mole crickets and their introduced BC agents. Discuss the impacts of invasive insects and how research could provide ecological, agricultural, and economic benefits.
c. Train students on morphometric data collection. Collect data by measuring mole cricket morphological traits for a grade (completion of assigned work and accuracy) during labs and as homework.

Research Output. After describing the methods, equipment, and technology available to the students (Rohde et al. 2019), we came up with research questions that could be answered during the semester and methods to do so. Starting in Week 2 and for the next 11 weeks, students learned how to search scientific literature and interpret research results, and they improved their writing skills and learned how to write a scientific manuscript.

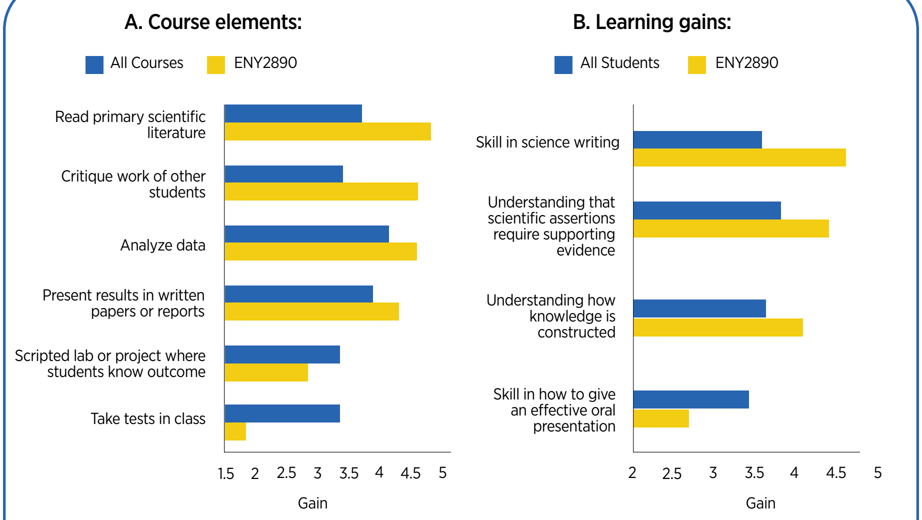

Fig. 2. Self-rated benefits to development and post-course gains to skills and abilities reported by students. A rating of five is the highest gain, and one is the lowest gain. The yellow bars represent mean ratings of the students in the present study (our course, ENY2890; ten students). For comparison, we also show the overall mean gains (blue bars) reported nationwide by students (from other CURE courses; 9,500 students) who took and responded to the same CURE survey between June 2016 and May 2017. This methodology was designed by David Lopatto (2004, 2008). For more details about its application in similar courses, see Miller et al. (2013) and Cirino et al. (2017).

Week 3 and Beyond: Balancing Manuscript Writing with Data Collection

Publishing a scientific manuscript in a peer-reviewed journal can be difficult. Therefore, writing a manuscript as an undergraduate can seem a colossal undertaking. Our strategy was to establish short-term goals, spread out writing assignments, and slowly increase the complexity of each task, while providing detailed peer-review style feedback on content and progress. Students had six writing assignments over the semester focused on "sperm storage in a true bug" in the following order:

1. Methods
2. Introduction
3. Introduction + methods + results
4. Full manuscript
5. Peer review
6. Final draft

Before the third assignment, we revisited the hypotheses of the sperm storage experiment, along with data exploration and visualization of the results using Excel. Students made their own manuscript figures, and the course instructor (P. Allen) performed the statistical tests and explained the findings. Learning to write a scientific manuscript was a valuable product of the course, as evidenced by the high-quality final drafts. The students' literature reviews were extensive, and segments of all students' final drafts were used in the final paper, Allen et al. (2018), which was published with the students as co-authors.

Beginning in Week 4, students began collecting data to fuel their second research project on invasive mole crickets. This project required collaboration between the class and co-author Dale's research lab. Dale's lab team deployed acoustic traps (Rohde et al. 2019), collected mole crickets from them weekly, and delivered them to the students, who imaged, measured, and surveyed them for parasitic nematodes (Fig. 1, right image). This course, with its collaborative dichotomous design, provided a logical and time-efficient framework to simultaneously train undergraduates to write a scientific manuscript (Research Project 1) and how to get to that point from the onset of a project (Research Project 2), all using authentic questions and data (Fig. 1).

Flipped-Classroom Approach

This course involved a high volume of in-class discussion and limited use of formal lectures. To guarantee that students were prepared for discussions, we used multiple approaches:

1. Take-home quizzes (due before class began). Quizzes were based on primary literature (Readings on the syllabus, supplemental material) associated with the assigned research projects. If needed, we referred to the quiz readings for discussion topics, helping the students comprehend the material and participate in discussions.
2. Allotted time to discuss both research projects. Every week, students and the instructor would discuss recent readings and/or writing assignments associated with Research Project 2. Every other week, the instructor presented an update on Research Project 2. When an issue arose in the field, the discussion would center around troubleshooting and the reality of field research. These, along with discussions about the structure and value of a well-written

manuscript and the ethics of accurate data collection, were the most valuable in providing students with an authentic research experience.
3. Discussions of short readings and videos about an important scientific topic. Topics included data storage, science in the media, science communication, the peer-review process, and how to submit a manuscript to a journal. These topics were debated or discussed in small groups and as a class.

Additional Gains for Students

Encouragingly, students reported strong gains in their understanding of the scientific process, critical thinking, and confidence as young researchers (Fig. 2). Below are quotes from students that highlight personal gains and suggest that this experience profoundly changed their perspective and appreciation for scientific research.

- "I felt like the process of being an undergraduate was just to learn huge volumes of information that I could not really put together. Once I got involved in the whole research process, I was able to backtrack, and everything made sense. You know these discoveries occurred because people were doing research on it. So now I wish I would have had this opportunity to take the class as a freshman."
- "I feel more confident in research because I learned wherever you do research it is a very collaborative effort, so you don't have to go into it having already mastered the field."
- "I admit prior to taking the class, I always knew that research was finding the answer to a question … but I never thought of it as having impact on other parts of our lives such as making government decisions or improving the economy."

One of the biggest testaments to the benefit of this course on students' views of STEM as a career option is that at the beginning of the course, only one student out of ten wanted to pursue a career in STEM, but by the end, there were four. After the conclusion of the semester, all students were invited to continue participating in data collection, science communication (via outreach events), and scientific writing to co-author a second scientific paper about Research Project 2. Four students received independent research credit hours to continue working on the project for the next two semesters. By the end of the second semester, the students had helped with a second field season, finished measuring all collected mole crickets, and co-authored their second scientific manuscript (Allen et al. 2020), which resulted from original research that began in their classroom.

Insight from the Instructors

Research experience as an undergraduate can be fundamental in shaping careers. Insects provide an engaging avenue to introduce undergraduates to the scientific method and the trials and tribulations of authentic research. This course successfully immersed students in the scientific method from beginning to end, resulting in co-authorship of peer-reviewed papers. To aid future course designers, we list here all the components of the scientific method that were independently discussed and addressed during this course (Fig. 1), providing a simple but comprehensive checklist on how we used the two independent research projects to fulfill each step of the scientific process. We used every course assessment (plus ungraded class activities) and discussion as opportunities for the students to develop skills associated with one or more components of the scientific method.

The substantial time investment in writing assignments by both students and instructors, as described above, was worth it. We found that student writing improved with instructor feedback, allowing a truly collaborative writing experience. The sometimes heavy editing and elaborate peer-review feedback by the instructor(s) parallels the job done by a lab leader (PI), with the same goals in mind: improving writing skills by the student/collaborator and a publishable scientific manuscript for all involved.

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