Creating an Interdisciplinary Research Course in Mathematical Biology[†]

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Name of Institution: University of Nebraska-Lincoln	
Size	about 24,000 students
Institution Type	large state university with PhD program
Student Demogaphic	recent high school graduates with high potential and interests in mathematics and biology
Department Structure	Mathematics and Biology are individual departments in the College of Arts and Sciences

Abstract

An integrated interdisciplinary research course in biology and mathematics is useful for recruiting students to interdisciplinary research careers, but there are difficulties involved in creating and implementing it. We describe the genesis, objectives, design policies, and structure of the Research Skills in Theoretical Ecology course at the University of Nebraska-Lincoln and discuss the difficulties that can arise in designing and implementing interdisciplinary courses.

Course Structure

- Weeks per term: 5-week summer session
- Classes per week/type/length: five 1-hour lecture periods each week
- Labs per week/length: five 1-hour laboratory periods each week
- Average class size: 8-14 students in one section
- Enrollment requirements: For high school students and university freshmen. Students must apply for the program and get a recommendation from a teacher.
- Faculty/dept per class, TAs: Team-taught by one mathematics instructor and one biology instructor, with the mathematics instructor doing the quantitative lecture portion of the lecture.
- Next course: The purpose of the course is to teach research skills. There are no related courses, but many of the students will do research projects later in their programs. Some students may choose to take additional courses in mathematics and/or biology, including interdisciplinary courses.
- Website: http://www.math.unl.edu/programs/rute/

Introduction

In 2005, I (Dr. Ledder) led an effort at the University of Nebraska-Lincoln to obtain a UBM (Interdisciplinary Training for Undergraduates in Biological and Mathematical Sciences) grant from the National Science Foundation. The principal purpose of the UBM program is to develop a cadre of undergraduate students who have developed the skills and interests needed to become productive interdisciplinary researchers in mathematical biology; accordingly, the chief component of our Research for Undergraduates in Theoretical Ecology (*RUTE*) program is the *RUTE Scholars Program*, in which teams of students and faculty mentors from both mathematics and life sciences work together on a research project. Because obtaining large competitive grants is a priority at our institution, we had the services of a team of consultants to help us polish the proposal. The consultants said that we needed a transition

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program for the period between when the students arrive on campus and when they are ready for the research program. With just two weeks before the proposal was due, I created a 5-week summer session course called Research Skills in Theoretical Ecology, whose purpose was to teach interdisciplinary research skills to lower division students. The word "created" is an overstatement because at that time the course was only a title and a rough idea. I had no idea what we would teach in it or even how to design it. That was a problem to face later. It was like jumping out of an airplane with a bag of material and expecting to build a parachute on the way down.

Our proposal was funded in October 2005. Research Skills in Theoretical Ecology was to be offered in early June 2006. All I had at the outset was a goal:

- Introduce *interdisciplinary research* in mathematics and biology to talented students *at an early stage* in their careers.

Assembling the Team

The crucial step was the first one: finding the right biologist to work with. The University of Nebraska-Lincoln had just hired Dr. Tenhumberg (for a joint appointment to the School of Biological Sciences and the Department of Mathematics, with tenure home in Biological Sciences), a theoretical ecologist who was interested in the project. There was a significant problem to face at the outset. As a new hire, with her tenure track appointment to begin in Fall 2006, she had to concentrate her energy on tasks that would strengthen her tenure file. Time spent during the summer teaching a course, rather than working on research, was not something that she could afford. This situation tested the commitment of our administration, which rose to the occasion. The School of Biological Sciences' department chair offered to count the course toward her teaching load for the following academic year, thus freeing time for research in the fall that would be equivalent to what she lost in the summer.

Interdisciplinary courses pose a significant staffing problem at most institutions. They can be taught by a single faculty member, but are then unlikely to be interdisciplinary in viewpoint. If taught by faculty from two departments, then each faculty member is likely to do as much work as for a full course, while each department is likely to count the work as only half a course. This problem was solved for the first year by the School of Biological Sciences' policy of counting a team course as a full course for each faculty member in the first run of the course and Dr. Ledder’s willingness to teach his part for summer pay equivalent to that for half a course. Subsequent years proved more difficult because we could not fully fund two faculty members to teach the course. After the initial offering, we saved some of Dr. Tenhumberg’s time by hiring a teaching assistant to help with the laboratory instruction. More of the workload shifted to teaching assistants: in 2009 and 2010, the biology component was taught by biology graduate students from Dr. Tenhumberg’s lab; in 2010, we turned the mathematics component over to a mathematics graduate student who had taken a modeling course from Dr. Ledder and had begun a research program in mathematical biology with Dr. Tenhumberg as co-advisor. These staffing arrangements worked because our graduate student teachers combined high levels of knowledge of the laboratory procedures needed for the experiments, the relevant biological literature, and the principles of mathematical modeling.

Objectives and Constraints

Most courses begin with a minimalist design process. We choose a body of material, then a text, then a syllabus, and then decide on the assignments. The course goal is generally implicit in our choices rather than a guiding principle for them. This is a blessing in that it makes the design quick and easy, but it is also a curse because courses so defined can be unfocused.

Since Research Skills in Theoretical Ecology was unlike any other course in our experience, we used an intentional design process, beginning with the course goal, progressing to a list of objectives, a list of outcomes, and finally a set of in-class activities and outside assignments. We started by deciding on our interpretation of key words and phrases in the course goal. By "interdisciplinary" we meant a unified whole with experimental biology and mathematical modeling as critical components, rather than biology augmented by statistical analysis, mathematics motivated by biology, or a loose confederation of the two. We intended the students’ work to be a serious attempt to investigate aspects of a single open-ended problem and reach conclusions supported by experimental data and mathematical modeling. Originally, we intended the course to be for students who had taken freshmen courses in biology and mathematics. Recruiting difficulties led us to pitch the course instead to talented students in the summer between high school and college, so we had to interpret "at an early stage" as meaning that we should not expect our students to have any laboratory experience or any useful knowledge of calculus or statistics.

We established three objectives for the course.

1. Learn knowledge and skills for theoretical ecology research.

2. Conduct theoretical ecology research.
    a. Collect laboratory data on ecological problems.
    b. Use the laboratory data to estimate the parameters of a mathematical model.
    c. Use the mathematical model to make predictions.
    d. Use additional laboratory experiments to test the model predictions.
    e. Draw appropriate conclusions.

3. Learn scientific communication skills.
    a. Read and discuss primary literature in ecology.
    b. Write scientific research papers/posters.

The structure of the course was dictated by these objectives. The course would have a lecture and a laboratory component, like most science courses, but the relationship between them was to be the reverse from what is usually done. Introductory science courses start with a body of material to be taught. This determines the lecture topics, and then the laboratory topics are chosen to supplement the lecture. Instead, the design of Research Skills in Theoretical Ecology would begin with a research agenda. This would determine the laboratory experiments, and then the lecture topics would be chosen to supplement the laboratory.

The chief constraint for the course had to do with the students. Straight-A students from a variety of high schools, with little or no college experience, have vastly different backgrounds. While we could expect that some of our students had studied calculus and some had studied ecology, we could not assume any specific background in biology, statistics, or mathematics beyond precalculus, nor could we assume any laboratory experience.

Design Principles

Our objectives and constraints resulted in a coherent set of design principles. We believe that the first five of our six principles could serve as design principles for any interdisciplinary research-based course in mathematics and biology, regardless of its level or content. We offer them as a general set of principles for research courses in mathematics and biology.

1. *The course should be about skills rather than content. Everything in it should be based on a coherent research plan.*

This principle reflects a paradigm shift that is occurring throughout education. General education in the 20th Century was almost universally thought of in terms of content. Distribution requirements are based on the principle that students need to know something about many different areas. In contrast, some new general education programs, such as the Achievement Centered Education (ACE) program (University of Nebraska-Lincoln, 2012a) that was implemented at the University of Nebraska-Lincoln in Fall 2009, are based on the principle that students need to develop important skills. Similarly, many institutions acclimate freshmen to academics with a freshman seminar course; such courses differ by institution, with many choosing interdisciplinary or nonstandard content, but they share the purpose of teaching freshmen the academic skills of careful reading, critical thinking, and writing.

2. *The research program should be both experimental and theoretical, with a clear focus.*

Science is a combination of theory and experiment, although individual scientists commonly focus on one or the other. Theoretical work needs to be firmly grounded in observation or else it is mere speculation. Experimental work needs to be informed by theory or else it is merely a collection of disjointed facts. The best way to teach science is to give students a course that integrates experiment and theory.

3. *The research program needs to be devised primarily by the biologist with the mathematician's approval*.

The biologist needs to have the laboratory expertise for the project, and the mathematician has to have to flexibility to devise a mathematics component to match the given biology component. This was an easy principle for us to follow, because Dr. Ledder's training is in mathematical modeling (see Ledder (2008)) rather than mathematics *per se*. Any mathematician working with a biologist on a research course needs to make the same concession. Mathematicians do not need specialized mathematical knowledge to write down population dynamics models for many different experiments, but biologists need in depth knowledge about the organisms being studied to be able to design quantitative experiments. It can be challenging to design research projects in which experiment and mathematical modeling go hand in hand. Dr. Tenhumberg's experience in constructing and using mathematical models facilitated our accomplishment of this goal.

4. *The course should be fully integrated: biology and mathematics, theory and experiment, laboratory and lecture.*

This is a crucial distinction between a research-based course and a knowledge-based course. In knowledge-based courses, it is not possible to support every theoretical statement with an experimental investigation, nor is it possible to plan a laboratory to match every lecture topic. In a research-based course, all the experiments have to be supported by theoretical work. Our motivation for integrating the biology and mathematics was to impress on students that there is a connection between these fields that they have probably always seen as unrelated.

5. *An authentic research experience must lead to a research paper, although the research need not be publishable.*

We have found that having to explain work in writing contributes to the student's understanding of the work (Ledder et al., 2013). Instead of a final exam, our students write a paper (in groups the first two years, individually thereafter) that looks as much like a professional research paper as they can manage. We get best results by having students write one section at a time, with feedback and rewrites of one section concurrent with the first draft of the next. We also devote time to examining professional research papers to discover scientific writing style and conventions.

6. *The course must be self-contained; it must provide the necessary biology background, teach the laboratory methods, build the mathematics up from a pre-calculus background, and teach scientific writing.*

This principle was required because of the uncertain background of our students. It might not be necessary for a course that is a capstone rather than an introduction. Even so, it is probably best to include too much background rather than too little. We found that talented students with a precalculus background could learn some matrix algebra and differential equations in population dynamics, provided that it was introduced appropriately (Ledder et al., 2013).

Discussion

The details of our research program, mathematics content, and pedagogy appear elsewhere. (Ledder et al., 2013; University of Nebraska-Lincoln, 2012b) Here we discuss the challenges one encounters when intimately-connected course components are designed and taught by people from different academic cultures.

- Notation and vocabulary

The first time we taught the course, Dr. Tenhumberg attended all of the mathematics lectures and Dr. Ledder attended all of the laboratory instruction sessions and some of the data collection sessions. This was helpful in standardizing the notation and vocabulary for the course. The next time we taught the course, we suffered from a bit of notation drift. Dr. Ledder used the symbol r for the *dominant* eigenvalue of a matrix so as to avoid using a Greek letter. Some of the mathematics literature uses r in this manner. He also used r for the relative growth rate in a differential equation model, which is standard in both mathematics and biology. For a mathematician, using r to mean one thing in the discrete context and something different in the continuous context causes no problem. Although the demographic literature is not fully consistent in notation, λ is typically used for discrete time models and r for continuous time models, so using r for both types of model is potentially confusing for students using textbooks written for biologists or primary literature. In retrospect, it is clear that notation should conform to biological standards as much as possible. Similarly, it is important to append biological names ("asymptotic growth rate") to mathematical names ("dominant eigenvalue").

- Software

For our first class, we used Excel for the statistical analysis because it is available on most student computers and all university computers. We used Matlab for programming simulations because it was already installed on the computers in the mathematics computer classroom. Most of our students did not want to purchase a Matlab license just for this course, which meant that they had to do all their programming in department facilities. In the second year, we instead tried Octave, which is free and similar to Matlab, but it did not work well in Windows and we went back to Matlab. In the third and subsequent years, we used R (R Development Core Team (2012)) for statistics and programming, and this turned out to be an excellent choice. R is popular among biologists, has similar functionality to Matlab, can be downloaded from the internet for free, and installs seamlessly in either a Linux or Windows environment.

- Data analysis and presentation

In the first year, we completed data collection before starting data analysis. We underestimated how long the data analysis would take because students were ignorant of the most basic statistics, like the normal distribution. Thus we resorted to using the built-in routines provided by Excel without a detailed explanation of the statistical methods. In the following years, we restricted the statistical analysis to a minimum, with instruction in statistical data analysis beginning in the second week of the course using simulated data (see Ledder (2013)). The students were happier with their understanding of statistics, but our requirement that they write their own statistics routines made them more intimidated by computer programming. We eventually lowered our expectations for the data analysis part of the computer programming while still requiring the students to write their own programs for simulations.

The style and conventions of research papers in mathematics and biology differ, which meant that we had to negotiate stylistic elements for student papers. Biology journals usually use author's name and year for citations, whereas many mathematics journals use a number corresponding to the reference list. We used the name and year method. Biology papers usually have an Experimental Methods section, which contains the mathematical models as well as the laboratory procedure. Mathematics papers usually have a separate Modeling section that does not easily fit into the structure of biology papers. We settled on following the biology structure because our research emphasized experimental work and the students were reading primary literature in biology. We extended the Experimental Methods section to include more mathematical content than is typical for biologists.

Conclusions

Differences in academic culture between mathematics and biology provide challenges to creating an integrated interdisciplinary course to teach research skills. Several design principles provide a basis for a research-based course designed and taught by a biologist and a mathematician: the course should focus on skills rather than content, be driven by a research agenda created largely by the biologist; integrate all components; and culminate in a written paper. Cultural differences need to be appreciated, but can be bridged through planning and communication. The resulting course can provide students with an authentic scientific research experience delivered as an academic course.

References

Ledder, G., 2008: An experimental approach to mathematical modeling in biology. *PRIMUS*, **18**, 119--138.

Ledder, G., cited 2012: BUGBOX Mathematical Modeling Simulations. [Available online at http://www.math.unl.edu/~gledder1/BUGBOX/.]

Ledder, G., B. Tenhumberg, and G.T. Adams, 2013: An interdisciplinary research course in mathematical biology for young undergraduates. This volume.

R Development Core Team (2012). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org/.

University of Nebraska-Lincoln, cited 2012a: Achievement Centered Education. [Available online at http://ace.unl.edu/.]

University of Nebraska-Lincoln, cited 2012b: Research for Undergraduates in Theoretical Ecology. [Available online at http://www.math.unl.edu/programs/rute/.]