Initial Steps Towards an Integration of Quantitative Thinking into the Teaching of Biology at a Large Public University

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Name of Institution	University of California, Davis
Size	32,000
Institution Type	Large comprehensive land grant university, offering bachelors through doctoral degrees, with four professional schools
Student Demographic	Students majoring in the life sciences
Department Structure	Life sciences courses are taught in sixteen departments in two undergraduate colleges, with mathematics, statistics, and computer science in separate departments in two other undergraduate colleges

Abstract

Faculty at the University of California, Davis, have addressed the need for integrating quantitative approaches in the biology curriculum by implementing new courses: an introductory two-hour per week modeling course and several one-hour per week quantitative "Q courses" associated with required upper division courses. The new courses are aimed at the general student population, are designed to be taught by biological faculty with minimal input of additional resources, and complement existing specialized modeling courses.

Course Structure

- Weeks per term: ten-week quarter
- Classes per week/type/length: one lecture per week in lower division course, with computer-based tutorial in all courses
- Labs: one hour computer lab per week, optional
- Average class size: up to 50 per section
- Enrollment requirements: lower division course: integral calculus (may be taken concurrently); upper division courses: any prerequisites that correspond to the accompanying lecture course
- Faculty/dept per class, TA's: coordinating faculty member plus one TA
- Next Courses: students who satisfy appropriate prerequisites may elect upper division courses on modeling in biology taught in life sciences, mathematics, or engineering departments
- Website: http://biosci3.ucdavis.edu/qcourses/

Introduction

All aspects of biology–the central ideas, the intellectual tools available, the practical methods used in the laboratory, the organization of research effort – have changed dramatically in the last two decades. This has great significance, because biology promises to shape human affairs in the 21st century as much or more than physics did in the 20th century. The changes have occurred so quickly that the way biologists are trained is ill-suited to the emerging reality of biological research, as virtually everyone in the business of biology, whether as a practicing scientist or as a

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teacher, agrees. Moreover, there is agreement about how undergraduate education must be transformed to prepare biology students for future research and discovery (e.g., see Association of American Medical Colleges and the Howard Hughes Medical Institute 2009; and National Research Council 2003).

Virtually every major problem in biology now requires the use of quantitative models, and the time is fast approaching when quantitative thinking will be as much a part of a biology degree as it is of a physics degree (Hastings and Palmer 2003; Levin *et al*. 1997, Marsteller 2010; Steen 2005). But there is a gap between the current reality and the inevitable future. At present, most biology students lack the familiarity and skills needed to apply or even to acquire the quantitative tools necessary for modern biological research. Many still regard calculus as a filter, rather than a pump that impels them toward success (Steen 1987). Because of this attitude and inertia, faculty members have generally been reluctant to introduce more quantitative material into biology curricula.

How do we get from here to there? This is the question we have tried to answer at the University of California, Davis. We believe it must be tackled at the undergraduate level. While it is admirable to have specialized classes in quantitative biology for graduate students and to cultivate a small cadre of gifted undergraduates acquainted with mathematics and biology, we need changes that affect the average student. Mathematical and physical principles must be seamlessly integrated with biology from the earliest stages of an undergraduate career (Bialek and Botstein 2004). Here we describe our first steps along that path.

At the University of California, Davis, we have introduced two types of new courses: an introductory two-hour (per week) modeling course for freshmen and sophomores and one-hour (per week) quantitative courses ("Q courses" in local parlance) associated with core upper division courses that build on the skills established in the two-hour introductory course. Both types of courses are aimed at the general student population, complement existing upper division modeling courses, and are designed to be taught by biology faculty with minimal input of additional resources. We developed the Q courses to accompany specific biology lecture courses by partnering with faculty who use models but do not regard themselves as quantitative biologists. In this paper, we explain the institutional context for our curricular renovations, describe the courses we have developed, and discuss the successes we have enjoyed and the challenges we continue to face.

The Institutional Setting

The University of California, Davis (UC Davis), is a large public research university that graduates over 2000 life science students every year. Curriculum changes at our institution and institutions like ours have a major impact on the future of national research (Hastings et al. 2002). Although research universities make up only 3% of the 3,600 colleges and universities in the United States, over 47% of the nation's college graduates receive their undergraduate degrees from a research university (Carnegie Foundation 2001).

The nature of our institution makes curricular change difficult. First, the size of research universities makes curricular change logistically complex (see also Nance and Kubatko 2012). UC Davis biologists are housed within five autonomous departments within the College of Biological Sciences, with nine undergraduate majors within that college. In addition, fifteen other majors in the College of Agricultural and Environmental Sciences can be considered as “life sciences.” Second, governance at our institution imposes a further constraint: power is decentralized and faculty and administrators share governance. Changes cannot be made by administrative fiat, no matter how visionary the administrators. Instead, large numbers of faculty must reach consensus. Third, like many institutions, we have limited amounts of time and money. New courses that require a large amount of faculty or teaching assistant time are not feasible.

In other ways UC Davis is well positioned for implementing a more quantitative curriculum. First, a substantial number of faculty within the life sciences are trained in both modeling and bench or field biology. Second, all life science majors at UC Davis must take a year of calculus, with biological calculus as an option. Most life science majors also take statistics, which can include a statistics course aimed at a biological audience. Third, we planned the quantitative courses as part of a larger revision of the biology curriculum. The revision entailed discussion and study that led to a document approved by the faculty of the College of Biological Sciences. Both faculty and administrators strongly supported developing an introductory modeling course for lower division biology undergraduates and augmenting upper division options that integrate biology with mathematics or computation.

Modeling in Biology: the Introductory Course

In Modeling in Biology, a two-hour per week introductory course, we show freshmen and sophomores how quantitative approaches can yield insight into biological problems. We seek to increase students’ comfort with quantitative ideas, rather than mastery of a set of skills. We use a practical and intuitive perspective rather than the abstract and rigorous approach taken in mathematics courses. We present mathematics and computation–specifically simulation, algorithms, elementary programming, and symbolic computations–to answer a specific biological question. Making a model to address the question may simultaneously answer it while raising others. The cycle of exploration and discovery helps students to think of science as a process and way of knowing (Moore, 1984) rather than as a collection of facts.

Offering the course to freshmen and sophomores has several advantages. We equip students with intellectual and practical tools to use throughout their undergraduate education. The course can also serve as a feeder for other academic programs, e.g., the NSF-funded Undergraduate Biology and Mathematics research program at UC Davis, or the minor in Quantitative Biology and Bioinformatics. Last but not least, this introductory course may broaden students’ research opportunities with faculty.

Our course is based around a software package called Mathcad (http://www.ptc.com/products/mathcad/). Mathcad can be readily mastered, uses notation similar to mathematical notation, and can integrate text, images, and computations in a single document. Mathcad is installed in computer labs on our campus and student versions are available under our license agreement for under $20. Students who purchase a license can complete coursework on their own computers. The licenses are valid indefinitely, giving students a powerful quantitative tool to use in future classes or in research.

The Modeling in Biology course implements many of the recommendations of the National Research Council (2003) for mathematics and computer science in biology curricula. Students gain skills in manipulating, processing, and graphically displaying data. They examine data for correlation and suggest experiments to test causation. Students carry out computer experiments to test biological hypotheses, and examine the relationships between theoretical constructs and experimental data.

The course consists of weekly lectures and six modules. Each module is based on a Mathcad file, similar in appearance to a word processor document. Each module (see Table 1) includes goals, background about the biological question, instructions, prompts for student work that completes the Mathcad document, and solutions so students can check their work. Modules are independent so instructors can vary their order or add new modules. Module assignments vary from one to two weeks in duration, with about three hours of student effort per week. A weekly lecture by the instructor sets the context for the module and student discussions (for a discussion of this approach, see Boyer Commission (1998)).

Table 1. Content of modules used in the course Modeling in Biology

Module	**Topic**	**Quantitative skills and ideas**	**Biological examples and ideas**
1	Introduction to Mathcad	functions, sequences, graphing, scaling	population growth, biomechanics, caffeine metabolism
2	Manipulating data	arrays, Boolean operations, fitting a line to data, correlation vs. causation	beetles and tree ecology
3	Probability and stochastic behavior	probability, stochastic behavior, manipulating arrays	ion channels
4	Rates of change	differential equations	population growth, HIV, ion channels
5	Scaling	data plots (arithmetic, semi-log, and double-log)	scaling, brain size, allometry
6	Sex lives of primates	integrating skills previously introduced	mating systems
7	Protein sequences	matrices, bioinformatics, public database access	amino acid sequences, homology, phylogenetic trees

Each problem is presented step-by-step, with regions of text and instruction interspersed with regions where students generate computations and document their interpretations. Figure 1 shows excerpts from a module on membrane ion channels. Because we assume no prior knowledge of either ion channels or the mathematics used to model channel opening and closing, the module includes information about both, and instruction in modeling. As the student works through the module, instructions become less specific. Each module culminates with a problem in which the student is given only a general description of how to solve it.

[ed: begin Figure 1]

Now that you've worked with the **if** function a bit, let's use it to create a new **state** vector that tracks the open/closed state of our single channel.

Enter the formula below, then go through it to make sure you understand how it corresponds to the statement described above:

$$state_t := if\left(state_{t-1} = 1, rnd(1) \geq 0.01, rnd(1) \geq 0.99\right)$$

4.04

$$state_t := if\left(state_{t-1} = 1, rnd(1) \geq 0.01, rnd(1) \geq 0.99\right)$$

Remember how we broke the transitions down into a list of events (1a, 1b, etc.) for the barking dog example above? In the space below, do the same thing for the expression you just typed, including the probability of each event. It's kind of tricky to understand, so take your time. Start by considering what can happen if the channel was open at time t-1, and then consider what can happen if the channel was closed at time t-1.

4.05

Plot your **state** vector, and see if it looks reasonable. Click on the blank region below and create a new x-y plot of $\mathbf{state_{time}}$ against **time**. Adjust the y-axis to range from **-1** to **2** instead of the default.

4.06

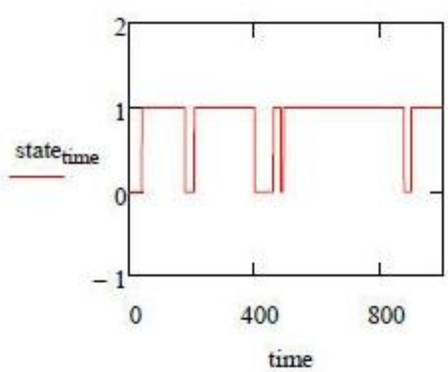

Figure 1: Excerpt from a module used in Modeling in Biology.

In all modules, we present information (beige) and instructions for an action that the student is to perform (blue). Students type their responses into white regions of the Mathcad file where calculations are immediately computed by Mathcad. In the example of a completed module, students use random events and Boolean logic to model ion channel opening and closing**.** After an introduction to Boolean logic, students create a number sequence (a vector, in Mathcad's terminology) that describes whether a membrane channel is open or closed. They graph the values versus time and compare the graph to experimental recordings of a single ion channel. For the complete module, see the Ion Channels module at http://biosci3.ucdavis.edu/qcourses/.

Student Support and Assessment

Students who have difficulty with parts of a module have several options for assistance. Students can work on the module during a designated laboratory period in a computer lab with the instructor and teaching assistant (TA). Students can also email the faculty member and TA with questions. In several offerings of the class we have arranged for virtual office hours in which the TA is available at designated times to interact online with students who have difficulties with the material.

Students upload completed modules to a secure server for grading. The TA grades a subset of pages within each module. Corrections and grades are noted directly in the Mathcad file, and the modules are returned to students electronically. A key is later posted in pdf format. We feel that posting a key is important, but we take two steps to minimize cheating by subsequent students. First, the key shows all the correct mathematics, but omits answers to essay-style exercises. Second, math regions in the key do not produce functional math regions if copied directly into Mathcad.

Grades in Modeling in Biology are based on work on the modules, results of an in-class midterm, and a final examination. We cannot administer a computer-based examination to large classes, so exams are on paper, instead of a Mathcad document.

Subsequent Revisions: Modeling in Biology

The initial implementation of Modeling in Biology consisted only of lab sessions. After the first offering, we modified the curriculum and course structure. Students acknowledged that the modules familiarized them with the tools of modeling, but they requested more direction about which tools to choose for a new problem. As a response to this, we added a weekly one-hour lecture in which the instructor presented examples of different approaches to modeling and their advantages and drawbacks.

We found that the style of the modules evolved through revisions of the course material. Initially, we included instructions that mostly consisted of keystrokes and verbal descriptions of results. We subsequently included screencapture images that depict the formula or graph that results from the appropriate keystrokes. They provide students with a less mechanical and more integrative view of the modeling process.

We discovered that many students needed reminders of how to perform Mathcad tasks they had learned several weeks earlier. Rather than including details of these procedures each time they arose in a module, we created short tutorials. We refer to these mini-modules as needed.

Finally, we found that students' mastery of computational skills improved when we included a short midterm exam. To reduce the demands on instructors, we created a bank of test questions from which faculty can draw.

On the whole, Modeling in Biology has gone well. Students seem to like the course and say that they intend to use their new quantitative skills in upper division courses. Two faculty members have requested to teach the course, and we offer it in winter and spring quarters. Three students from Modeling in Biology have gone on to take additional modeling courses, with one participating in a collaborative mathematics and biology training grant.

Upper Division Courses

In addition to the introductory course, aimed at lower division students, we sought to integrate similar content in large-enrollment upper division courses. A difficulty is that each course is taught by many instructors, with varying degrees of quantitative backgrounds and little incentive to come together to coordinate the effort required for course redevelopment. We avoided it by developing one-hour per week adjunct courses–Q courses–to run concurrently with upper division courses (referred to as parent courses). The Q courses complement the parent course with quantitative treatments of topics covered in it. We have completed modules to accompany parent courses in animal behavior, biochemistry, biomechanics, and neurobiology. They are large-enrollment courses (from 120 to over 400 students per lecture section) offered every quarter.

Like the Modeling in Biology course, the Q courses exist as a series of Mathcad modules in which students complete a series of exercises. The background biology and context for the Q course is covered in the parent course's lecture. There is no separate Q course lecture. Completed modules are submitted to a teaching assistant, who grades a subset of exercises and posts a key as in the Modeling in Biology course. Participation in the Q course by the parent course instructors is at their discretion.

Our goal in developing Q courses was to provide a quantitative supplement to upper division courses. However, we soon found that the details of the goal were subject to interpretations by students and faculty that ran counter to our own vision.

The first myth we sought to dispel was that the Q courses were targeted at high-achievers who wanted to hone their already substantial quantitative skills. On the contrary, we see Q courses as being for all biology undergraduates.

Unfortunately, our attempts to dispel the myth generated another misinterpretation–that Q courses are designed to help students with the quantitative aspects of the parent course. Q courses probably do help students but they were not designed for that and may be an inefficient method.

Q courses have some goals independent of the parent course and others that depend on it. Regardless of the parent course, students gain experience using computer software, in particular Mathcad, to solve quantitative problems and visualize solutions. If a student is given a model (e.g., a set of equations), he or she should be able to use a computer to implement it and generate simulations. These are skills that continue naturally from the Modeling in Biology course.

In developing Q courses, we found that the parent course plays a large role in determining the other goals we can set. For example, our neurobiology Q course takes advantage of Mathcad's ability to solve ordinary differential equations, so students are able to construct the Hodgkin-Huxley model of the action potential and see the effects of changing model parameters (see http://biosci3.ucdavis.edu/qcourses). Prior to the Q course, the topic was treated only qualitatively or by demonstrating the model in class. In this case, the Q course has the purpose of putting the student in the driver's seat, getting them to construct the model, seeing the components involved, and understanding the quantitative role of the input parameters.

The qualitative nature of the neurobiology parent course contrasts with a more quantitative biochemistry parent course for which we developed a Q course. Many of the biochemistry models are of acid-base reactions that can be solved without a computer, given a single set of input parameters. However, the equations are non-linear. Students can calculate single points, but understanding how the equations behave is difficult. In the biochemistry Q course, students work with the models graphically, gaining an understanding in their mind's eye. Rather than calculating a solution at one pH value, they calculate the solutions at 100 pH values and use Mathcad's 3-D graphing abilities to calculate solutions over a 100 x 100 surface.

In the biochemistry parent course, models are already used and solved, so our goal is an understanding of the equations. In neurobiology, the equations are so daunting to begin with that simply playing with them provides major insight.

Subsequent Revisions: Upper Division

In planning the upper division Q courses, we consulted with faculty members teaching the parent courses and obtained their input. When possible, we made each module independent of others to accommodate individual instructors' scheduling preferences while allowing lectures to motivate and provide background information. Initially, we envisioned a close association between lecture and quantitative material so that students would enhance their understanding of lecture material by completing exercises in the Q course. This was not always possible in practice.

For example, notation varies between instructors. Students became confused when Q course notation differed from that used in the parent course. Further, when students from three different parent sections of biochemistry simultaneously enrolled in a single biochemistry Q course, we learned that we could not assume a tight connection between lecture and Q course modules. Faculty in the lecture sections covered material in different orders. As a result, some students were able to use modeling exercises to reinforce biological concepts that appeared on the midterm examination in their parent course, but other students saw this material in the Q course after their midterm examination.

This led us to decouple the Q course from the parent course. We gave students in the Q course notice that they might see modeling exercises on a particular topic in conjunction with, well before, or after their lecture course midterm examination. This means that modules, on average, are longer because of the need to introduce biological background information that would otherwise be provided by the parent course. We also encouraged students who had completed the parent course to take the Q course to enrich their knowledge of the parent course topics.

In general, faculty who have taught with Q courses have been pleased with the way the quantitative material complements the parent lecture course. Because of this, faculty members encourage students to take the Q course. To date, we have offered Q courses in biochemistry and animal behavior twice each and in neurobiology four times. The difference in frequency stems from the ability of the home department of the parent course to provide a TA to support the Q course. Until instructional resources become more available, it is unlikely that we will be able to offer Q courses regularly.

Assessment: Upper division courses

The structure of upper division Q courses provides a straightforward means of assessing one measure of their efficacy: the grade in the parent lecture course. We compared the lecture course grades of students who simultaneously enrolled in a Q course for a letter grade (neurobiology – two offerings with combined enrollment of sixteen; biochemistry – one offering with twenty-eight students) with lecture course grades of students who took the lecture course only in the same quarter (neurobiology, combined enrollment of 235; biochemistry, 674). Grades used in the analyses were converted to a 4-point scale: A=4.0, A-=3.7, B+=3.3, etc.

There appear to be no differences between Q course students and lecture-only students with regard to cumulative grade point average (GPA) at the start of the term. Q course students generally earned higher grades in the lecture course than students enrolled in the lecture course only; they averaged about 0.2 grade points higher (2.7 vs. 2.5). This result is similar for separate students in biochemistry and in neurobiology (Table 2). Further, the impact is greater for women than for men (Table 2) and for weaker students than stronger ones, based on aggregating students by cumulative GPA prior to the term. For example, students with cumulative GPA < 2.75 earned a course grade of 2.0 if enrolled in the Q course versus 1.7 if enrolled in the lecture course only.

Table 2. Percentages of students with a particular lecture course grade, based on enrollment in the lecture only vs. the lecture plus Q course, by gender (with courses pooled) and by course (with gender pooled). Sample sizes shown parenthetically.

	Men only		**Women Only**		**Biochemistry**		**Neurobiology**	
	Lecture only (n=402)	**Lecture & Q (n=20)**	**Lecture only (n=507)**	**Lecture & Q (n=24)**	**Lecture only (n=674)**	**Lecture & Q (n=28)**	**Lecture only (n=235)**	**Lecture & Q (n=16)**
D or F	10.1%	12.5%	12.4%	0%	11%	3.6%	11.5%	12.5%
C	37.1%	12.5%	30.1%	25%	32.8%	17.9%	37.4%	18.8%
B	38.1%	58.3%	39.1%	55%	40.8%	64.3%	31.9%	43.8%
A	14.8%	16.7%	18.4%	20%	15.5%	14.3%	19.1%	25.0%
GPA	2.5	2.6	2.5	2.9	2.5	2.8	2.5	2.7

Students enrolled in the Q course may outperform lecture-only students because they spend additional time each week on concepts associated with lecture material. Given student schedules with a full load of coursework and, in many cases, part-time employment and internships, it may be difficult for students to increase study time for a subject without the additional incentive provided by a course.

General Challenges

The biggest challenge to our curriculum revision has been the conflict between the desire of faculty to include quantitative instruction and the uncomfortable consequences of realizing that vision. For example, biology faculty members were initially enthusiastic about incorporating a lower division modeling course into the curriculum. However, when faced with the question of requiring the course for majors, departments were slow to make this curriculum change (see also Adler 2012). Possible reasons include reluctance to add requirements to an already difficult major or modify existing major requirements to make room for a quantitative requirement; a perception that the course is not germane to a particular major; concern that incorporating what students may perceive as a math course will drive math-phobic students into a similar major in another college within our university.

Similarly, our faculty members were initially eager to augment our upper division offerings with the Q courses but departments lack the funds to assign teaching assistants to the Q course.

Our choice of software, Mathcad, has presented us with successes and challenges. The look of Mathcad documents is reassuring to students. Equations written in Mathcad look more or less like equations on paper. Even complex operations like solving ordinary differential equations can be accomplished visually, without anything that looks like a program. Problems often can be framed in ways that make the most intuitive sense, rather than in the way that is most efficiently processed. A generous student discount establishes Mathcad as an affordable tool for students to use beyond our courses.

However, Mathcad has its drawbacks. We intended to use a worksheet protection feature to prevent students from editing or copying anything more than their own answers in the modules but it was so bug-ridden that we had to abandon our plan. Other Mathcad bugs forced us to include workarounds and other inefficiencies in the modules that distract from the teaching.

Alternatives to Mathcad include Matlab, Excel, R, XPP, Mathematica, and Maple, and there are many criteria on which we could base our software choice, such as ability to do mathematics beyond arithmetic computations (e.g., solve differential equations), ease of use, quality control (i.e., lack of bugs), availability on multiple platforms, cost to students, and popularity (i.e., likelihood it will be used in post-graduate employment). With so many factors potentially affecting our choice of software, it is easy to lose sight of the primary goal of the courses: *to develop quantitative thinking in biology.* The most important consideration is how well a software package can facilitate that goal. We are not training students to use a particular software platform to enhance their marketability. We are teaching them to think quantitatively. In the 21st century, that involves computer software training; but this is a means to our end, not an end in itself.

We have exerted considerable effort to convince others (and ourselves) that Mathcad is the right platform to use for our courses. Faculty agree that students would be well-served by proficiency in one platform used across many classes. However, confidence that Mathcad is the best platform to choose is so far lacking, and the issue of which to use is often revisited. The unfortunate truth is that we have to choose, and there will always be those who disagree with our choice.

Conclusions

On the whole, we are pleased with our curricular revision. The lower division modeling course and upper division Q courses provide the general undergraduate population with a biological introduction to quantitative thinking. Because the Q courses are separate, we were able to develop a more quantitative curriculum without having to revise existing lecture courses. However, our efforts to integrate these courses into the biology curriculum have been thwarted by the zero-sum nature of unit requirements, as well as the hyper-democratic and resource-limited environment of our university. While faculty widely agree that quantitative treatments should be added to the biology curriculum, they widely disagree on what should be removed to make room for these.

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