Teaching quantitative biology: goals, assessments, and resources

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ABSTRACT More than a decade has passed since the publication of *BIO2010*, calling for an increased emphasis on quantitative skills in the undergraduate biology curriculum. In that time, relatively few papers have been published that describe educational innovations in quantitative biology or provide evidence of their effects on students. Using a "backward design" framework, we lay out quantitative skill and attitude goals, assessment strategies, and teaching resources to help biologists teach more quantitatively. Collaborations between quantitative biologists and education researchers are necessary to develop a broader and more appropriate suite of assessment tools, and to provide much-needed evidence on how particular teaching strategies affect biology students' quantitative skill development and attitudes toward quantitative work.

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> Quantitative analysis, modeling, and prediction play increasingly significant day-to-day roles in today's biomedical research. To prepare for this sea change in activities, biology majors headed for research careers need to be educated in a more quantitative manner.
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> *BIO2010* (National Research Council, 2003, p. 41)

Most publications touching on quantitative biology in education highlight concerns about the state of biologists' quantitative skills, call for action to change biology education to emphasize quantitative skills, or make bold recommendations for how to build the quantitative expertise of the next generation of life scientists (summarized in Labov *et al.*, 2010). Rather than restating these compelling arguments, we wanted to bring attention to existing resources for teaching quantitative biology and for documenting the impact of teaching more quantitatively.[1]

In contrast to the numerous opinions and editorials on the topic, relatively few articles offer concrete, specific descriptions of instructional strategies or curricula aimed at helping life sciences learners develop quantitative skills. Even fewer articles include data showing efficacy of these approaches. For example, 117 papers have cited *BIO2010*, a leading National Research Council (NRC) report calling for the development of undergraduate biology students' quantitative skills (NRC, 2003), but < 15% of these describe an educational innovation that aims to develop biology students' quantitative skills. Similarly, of the 170 papers citing Bialek and Botstein's proposal of a fully integrated quantitative science curriculum (Bialek and Botstein, 2004), only a handful offer practical advice or resources for teaching biology quantitatively. *CBE—Life Sciences Education* (*LSE*), the sister journal of *MBoC*, is one of the few journals that have published descriptions of strategies for teaching quantitative biology accompanied by evidence of efficacy.

Before we can begin to make use of resources published in *LSE* and elsewhere, we need to articulate our goals. In other words, what do we want students to know, be able to do, or otherwise get out of educational experiences related to quantitative biology? We can then decide what evidence we will look for that demonstrates our goals have been achieved and how we can collect that evidence—or how we will conduct assessment (Tanner and Allen, 2004). Finally, we can select our teaching strategies to align with our goals and assessments. This entire process is called "backward design" (Wiggins and McTighe, 2005; Allen and Tanner, 2007) and is an effective way to design instruction to maximize student learning.[2]

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Abbreviations used: AAMC, American Association of Medical Schools; HHMI, Howard Hughes Medical Institute; NRC, National Research Council.

[1]Given space limitations, we opted to focus strictly on the intersection between biology and mathematics or statistics, although an increasing number of resources are being developed for teaching at the intersection of computation or physics and life sciences. For more on this, see the special issue of *LSE* on the integration of physics and biology education: www.lifescied.org/content/12/2.toc.

[2]For more on backward design, see *Scientific Teaching* by Handelsman *et al.*, (2007).

GOALS: WHAT ARE WE AIMING FOR IN TEACHING QUANTITATIVE BIOLOGY?

In a 2009 report, the American Association of Medical Schools (AAMC) and Howard Hughes Medical Institute (HHMI) articulate goals for quantitative biology teaching that can serve as a starting point. Specifically, biology students should be able to

- demonstrate quantitative numeracy and facility with the language of mathematics,
- interpret data sets and communicate those interpretations using visual and other appropriate tools,
- make statistical inferences from data sets,
- extract relevant information from large data sets,
- make inferences about natural phenomena using mathematical models,
- apply algorithmic approaches and principles of logic (including the distinction between cause/effect and association) to problem-solving, and
- quantify and interpret changes in dynamical systems (AAMC and HHMI, 2009, pp. 22–24).

Although these quantitative skills are critical, we propose that other skills inherent to being a quantitative biologist may be equally important, such as the ability to collaborate across disciplines (e.g., Hackett and Rhoten, 2009; Milton *et al.*, 2010). We also posit that engendering positive student attitudes about quantitative work is important, because students' interests and values, as well as their emotional responses, such as anxiety or enjoyment, can have significant effects on their willingness to engage in learning activities, persevere when they face difficulties, and persist in certain educational or career paths (Steiner and Sullivan, 1984; Glynn *et al.*, 2007; Rheinlander and Wallace, 2011; Matthews *et al.*, 2013; Poladian, 2013). Finally, we anticipate that positive skill and attitudinal outcomes will likely lead to desirable behavioral outcomes, such as enrollment in additional quantitative courses, completion of more quantitative degree programs, and pursuit of further education or careers in quantitative biology. Thus, we propose that our goals for students should go beyond development of quantitative skills to include

- more positive emotional responses to quantitative work, such as greater enjoyment or reduced anxiety;
- more positive beliefs about the ability to do quantitative work, such as increased confidence and self-efficacy;
- increased interest in quantitative work;
- greater sense of the centrality of mathematics, statistics, and computation to the practice of life sciences, including their relevance and importance;
- improved ability to work in interdisciplinary teams; and
- increased intentions to pursue or actual pursuit of further education and careers in quantitative biology.

ASSESSMENT: HOW DO WE KNOW QUANTITATIVE BIOLOGY TEACHING "WORKS"?

Just as data are needed to support hypotheses and conclusions in science research, data are needed to support the contention that students are benefiting from instruction. In particular, educational data should be collected to demonstrate whether students are making progress toward achieving the intended goals. What can students to do to convince us that they can use statistical methods to make inferences from data sets? How can we be sure that students understand the theory behind a mathematical model of a biological phenomenon and can use that model to make predictions? How will we know that students are less anxious about tackling quantitative problems or that they see math as relevant to their work as biologists? We must collect assessment data, such as students' solutions to problems, explanations of results or phenomena, or analyses and models of data. Published methods for assessing students' development of quantitative skills and other important outcomes are fairly limited. A number of assessments of quantitative reasoning or quantitative literacy have been developed, primarily to document quantitative skills of non–science majors (e.g., Steele and Kilic-Bahi, 2010; Sundre and Thelk, 2010). Similarly, attitudinal assessments have been developed primarily for general audiences rather than biology majors (reviewed in Chamberlin, 2010). More tools are needed to document students' progress toward quantitative biology–related outcomes, especially beyond introductory or non–majors biology. To this end, we encourage teams of biologists, quantitative scientists, and education specialists to collaborate in developing and testing a broader suite of assessment tools related to quantitative biology.

Assessments are much more than homework problems or exams—they are data-collection tools. It is not necessary, or even desirable, to always use published assessment tools when we teach, since these tools may not align with our teaching goals. Just as in science, educators often have to develop tools or techniques to address the task at hand. We can use results gathered from these tools to inform what and how we teach—a process called formative assessment. So how do we design formative assessments that are useful in quantitative biology instruction? Others have offered very useful advice on designing assessments (Angelo and Cross, 1993; Sundberg, 2002; Tanner and Allen, 2004). We will highlight just a few ideas here that are easily adapted to teaching in any domain.

To identify areas of confusion, we can periodically hand out index cards near the end of class and ask students to write one thing they learned and one thing they are still confused about. We can quickly peruse student responses and address the confusing ideas directly during the next class. We can also give challenging problems for students to work on or data sets to analyze, either as homework or in class, alone or in groups. We need to select these problems carefully to align with learning goals and give students practice solving the kinds of problems they will be expected to solve on exams or other high-stakes assessments. Students earn a small amount of credit (e.g., a few points for genuine, on-task effort) for completing the work before we discuss it as a whole class. We can ask students to share how they went about tackling the problem or conducting the analysis, what their results are, and where they ran into difficulties. We can then offer guidance as needed.

TEACHING STRATEGIES: HOW DO WE TEACH QUANTITATIVELY?

With goals and assessments in mind, we can choose what and how we will teach. Some resources we can adapt or adopt for use with our own students are already available. Some educators have developed entire research projects, courses, or course series (e.g., Edelstein-Keshet, 2005; Chiel *et al.*, 2010; Duffus and Olifer, 2010; Miller and Walston, 2010; Rheinlander and Wallace, 2011). For example, the SYMBIOSIS curriculum at East Tennessee State University is a tightly integrated, three-course sequence that replaces the standard Introductory Biology, Introductory Statistics, and Calculus I requirements. An initial assessment of the first two cohorts demonstrated student gains in both mathematical and biological knowledge, and further assessment is planned (Depelteau *et al.*, 2010).

Resource	Description	URL
BioMathLab	"Discovery-based" laboratory exercises that integrate biology and mathematics	www.indiana.edu/~oso/lessons/BioMath/BioMathLab.html
BioQUEST	The BioQUEST library contains more than 40 modules, many of which have quantitative components.	http://bioquest.org
	The BioQUEST ESTEEM project features math–bio modules that utilize Excel spreadsheets.	http://bioquest.org/esteem
General Biology Modules	University of Tennessee–Knoxville's list of modules aimed at promoting quantitative literacy in the life sciences	www.tiem.utk.edu/~gross/bioed/modulelist.html
MathBench Biology Modules	Online learning modules, primarily designed for introductory biology	http://mathbench.umd.edu
Mathematical Modelling of Natural Phenomena	Vol. 6, iss. 11 (2011) is a special issue on biomathematics education, featuring a number of math–bio activities to implement	http://journals.cambridge.org/action/displayIssue?decade=2010&jid=MNP&volumeId=6&issueId=06&iid=8400206
National Numeracy Network	A professional organization with a page highlighting educator resources, including teaching activities	http://serc.carleton.edu/nnn/teaching/index.html
PRIMUS	Vol. 20, iss. 2 (2010) is a special issue that contains descriptions of math–bio activities.	www.tandfonline.com/toc/upri20/20/2#.U8QH1o1dUs0
Science Education Resource Center at Carleton College	A collection of teaching resources, including a quantitative thinking section; contains more than 450 biology activities	http://serc.carleton.edu/index.html

TABLE 1: Web and journal resources for teaching quantitative biology.

Introductory courses have also been created that focus on learning the process of science, with data analysis as the main quantitative element (e.g., Bell, 2011; Goldey *et al.*, 2012). At the upper level, math–bio courses such as bioinformatics, mathematical biology, and mathematical modeling have been developed with the aim of bringing biologists, computational scientists, and mathematicians together to learn from one another (Hydorn *et al.*, 2005). Others have launched collaborations between upper-level math and biology classes for students to learn from one another as they work together on a math–bio project or problem (Greer and Palin, 2012).

Most of us don't have the time, resources, or inclination to develop an entire course. Instead, we can teach more quantitatively by using single lessons or modules that emphasize quantitative outcomes (e.g., Jungck *et al.*, 2010; see also Table 1). The *American Biology Teacher* contains numerous quantitative biology activities scattered throughout their issues, but *LSE* is especially useful for finding evidence-based instructional strategies and curricula. For example, Speth and colleagues (2010) infused data-driven problems and quantitative tasks into their ecology and evolutionary biology course, which led to improvements in students' abilities to represent data graphically. A number of websites feature collections of quantitative modules (see Table 1). One of these sites, MathBench, was developed by biologists at the University of Maryland and includes 30+ freely available online math–bio modules that can be integrated into existing life sciences courses. Thompson and colleagues (2010) have shown that students who complete these modules report gains in their quantitative skills and increased comfort with solving quantitative problems.

Challenges of teaching quantitatively include fitting quantitative elements into an already-packed curriculum and convincing colleagues that a new version of an existing course serves students as well as what has been done in the past. Concerns about failing to cover content may be assuaged by work from Hester and colleagues (2014), who demonstrated that students in a quantitative introductory molecular and cell biology class scored equally well on biology test questions when compared with students who completed a traditional content-driven class. They stress the importance of using a learner-centered approach to achieving such outcomes. Indeed, results from numerous meta-analyses (e.g., Freeman *et al.*, 2014) demonstrate that science students perform better when taught using active-learning approaches in place of traditional lectures—in other words, when instructors stop talking and engage students in tasks that promote meaningful, intellectual engagement (Allen and Tanner, 2005).

CONCLUSIONS

To prepare future generations of life scientists to take full advantage of mathematics and computation to understand the living world, we need to change how we are teaching. Start by articulating goals for quantitative biology instruction—consider quantitative and other professional skills as well as attitudinal outcomes, as all are important for developing expertise in quantitative biology. Then define the evidence needed to show that students have made progress toward achieving the goals and how this evidence will be gathered through assessments. Finally, design instruction to align with goals and assessments. Some quantitative biology curricula and assessments are already available, but new resources are needed and should be developed through the collective efforts of quantitative biologists and education specialists.

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