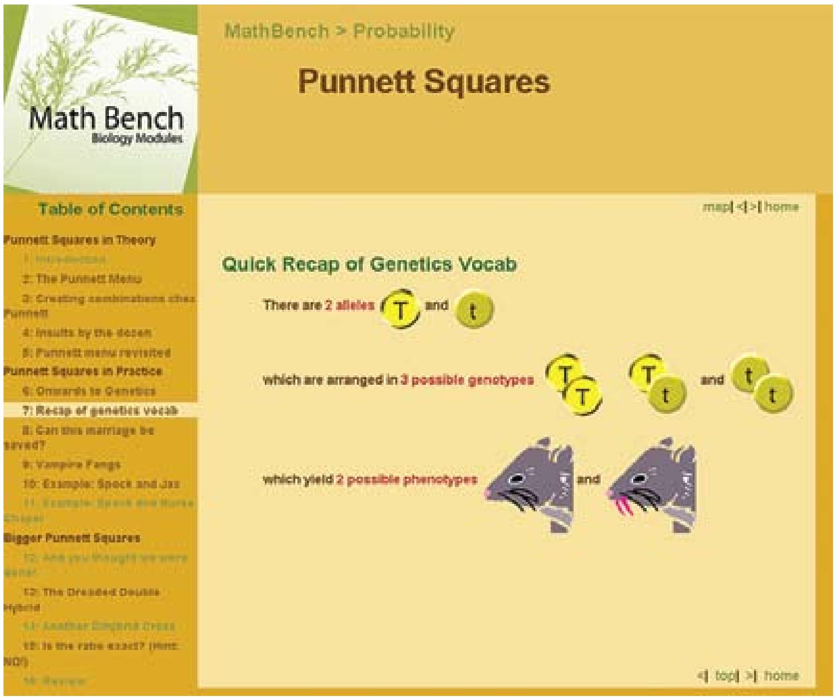
MathBench Biology Modules

Web-Based Math for All Biology Undergraduates

By Kären C. Nelson, Gili Marbach-Ad, Katie Schneider, Katerina V. Thompson, Patricia A. Shields, and William F. Fagan

In this series of interactive, web-based modules, students are introduced to the mathematical underpinnings of introductory biology in an informal but powerful way.



Historically, biology has not been a heavily quantitative science, but this is changing rapidly (Ewing 2002; Gross 2000; Hastings and Palmer 2003; Jungck 2005; Steen 2005). Quantitative approaches now constitute a key tool for modern biologists, yet undergraduate biology courses remain largely qualitative and descriptive. Although biology majors are often required to take a full year of calculus, these courses generally use examples unrelated to biology (Gross 1994) and ignore fields of mathematics that may be more relevant to biology, such as linear algebra or theoretical probability and statistics (NRC 2003).

Consequently, reform of the undergraduate biological science curriculum is urgently needed (NRC 2003; Steen 2005). However, there are significant barriers to integrating more quantitative approaches. Students have a reputation (deserved or not) for opposing the addition of mathematical content, and many professors are likewise uncomfortable with negative reactions and lack of mathematical mastery they perceive among their students (Yuan 2005; Jungck 2005). Finally, even when students have mastered both biology and mathematics, the connection between the two is problematic (Gross 1994; Jungck 2005). Math courses are rarely taught in a way that facilitates the ability to transfer mathematical knowledge to real-life, open-ended situations, still less to problems specifically involving the biological sciences.

The problematic connection between math and biology has been evident at the College of Chemical and Life Sciences at the University of Maryland, a large, public, Research I university. Surveys of our faculty indicated that they wanted to make their courses more mathematically rigorous but hesitated to do so because they feared students would respond negatively or would not be adequately prepared for a more quantitative approach. Nonetheless, there was consensus among faculty that tighter integration of biology and mathematics would better prepare our students for scientific careers. We designed these modules to provide tighter integration in a way that does not require instructors to substantially revise their courses. Mathematics can be integrated in a systematic way across the curriculum so that students experience a progression of instruction that builds both their quantitative reasoning skills and their confidence.

We began by assembling a list of "metaconcepts"—mathematical skills and concepts to be emphasized (Table 1), drawing from precalculus mathematics exclusively, because many students enrolled in introductory biology have yet to complete calculus. We then worked with faculty teaching introductory biology courses to identify the best places to introduce or reinforce mathematical concepts within the existing syllabus. Using this information, we developed the MathBench Biology Modules, a suite of interactive, web-based modules that supplement existing course content across the first two years of the biological sciences curriculum. Undergraduate biology majors will encounter 25 to 30 modules over the course of their first five fundamental biology courses. The modules cover a variety of topics but focus repeatedly on a core set of skills and concepts. Thus, MathBench makes quantitative approaches accessible and relevant to all students enrolled in biology courses.

Designing the modules

In designing the modules, we considered three key findings from the science education literature:

- *Many college students have trouble with quantitative work because of "math anxiety"* (Betz 1978). The modules are written in uncomplicated, colloquial speech, following numerous studies showing that a "personal voice" fosters deep learning while minimizing anxiety (d'Ailly, Simpson, and MacKinnon 1997; Mayer et al. 2004; Ross and Anand 1987). The modules also provide carefully structured repetition of key concepts, which has been shown to reduce math anxiety (Betz 1978) and "cement" mathematical knowledge (Bahrick and Hall 1991). In addition, many students are troubled not by the mathematical content itself, but by the application of mathematical content to biological problems—that is, by the transfer of knowledge to a novel problem (Mayer 2002). We therefore contextualize the information by embedding the quantitative work within engaging storylines. We couch all problems within the modules in terms of specific biological situations or everyday life, and explicitly teach the skills needed to distill mathematics from real-life situations.
- *Computers must be used to facilitate active learning, not simply present repetitive drills* (NRC 2003; AAAS 1993; Mayer 2002). Simulations and intelligent feedback isolating student errors play a vital role in helping students bridge concrete and abstract reasoning (Berger 1984; Ellis 1984; Mayer 2002). However, it is important that students do not simply watch a simulation, but actively construct knowledge by making predictions about the simulation beforehand and modifying their predictions after observing the simulation (Reed 1985; Wender and Muehlboeck 2003; Tversky, Morrison, and Betrancourt 2002). We create an environment in which students can use interactive pieces as tools to further learning and exploration.
- *Computer-assisted instruction can be individualized using "program control" (PC) and "learner control" (LC)* (Hannafin and Sullivan 1996). LC techniques allow learners to determine the amount of instruction and practice they prefer, while PC techniques determine via pretests the material to be presented. Learner control has been found to have a positive effect on student motivation, but it may also compromise learning for weaker students, who tend to skip over extra instruction and practice. We attempt to balance the legitimate ability of some students to skip large sections of the more elementary content within the modules with the needs of others to receive more explanation and opportunities for practice.

TABLE 1

The 10 metaskills and concepts taught in MathBench Biology Modules.

1. Distill biology into math—Parse verbal descriptions into mathematical equations.
2. Use equations—Manipulate equations by plugging in values or solving for a variable.
3. Use graphs—Create, interpret, and manipulate different types of graphs.
4. Fundamental equations—Recognize and use fundamental equations, including linear, exponential growth/decay, and power law.
5. Magnitude—Understand geometric scales and the representation of magnitude using scientific notation and log values.
6. Unit conversions—Convert units and use unit analysis to check answers.
7. Probability—Make simple probability calculations and understand stochastic processes.
8. Statistics—Understand the logic and calculations behind common statistical expressions (mean, variability, *p*-value) and tests (*t*-test, chi-square).
9. Model structure—Understand how mathematical models are structured, and how they differ (i.e., discrete versus continuous, stochastic versus deterministic).
10. Rates and equilibrium—Recognize rates of change algebraically and graphically and understand how change can lead to equilibrium.

The metaskills and concepts list provides a cohesive core to the effort. These are revisited in varying combinations and with increasing mathematical sophistication in 26 modules spread throughout the five-course introductory biology curriculum.

Description of the modules

Each MathBench module consists of 10–25 "pages" (a page is generally about one screen) of text, graphics, and interactive elements, and is designed to require one to three hours for students to complete. The modules progress from a review of previous knowledge (1–3 pages) to an intuitive introduction to new concepts (5–15 pages) and applications (3–8 pages). Each module contains one or more interactive applets (small, web-based computer programs) that allow students to explore key mathematical concepts and practice mathematical approaches. Each module concludes with a review and quiz to assess student learning. MathBench Biology Modules are used in five large-enrollment introductory biology courses taken during a student's freshman and sophomore years: BSCI 105/106/207 (the three-semester introductory biology sequence), BSCI 222 (Principles of Genetics), and BSCI 223 (General Microbiology). Table 2 lists the modules used for each course and the metaconcepts covered in each module.

Below we walk through one specific module, entitled "Introduction to Punnett Squares: Counting

TABLE 2

Modules in the MathBench biology suite.

MathBench Biology Modules	First Use	Distill Biology into Math	Use Equations	Use Graphs	Fundamental Equations	Magnitude	Unit Conversions	Probability	Statistics	Model Structure/Iteration	Rates & Equilibrium
Introductory Biology: Cell Biology											
Vis Measurements and Linear Functions	6/07	x	x	x	x		x				x
Stat: Normal Distributions and the Sci. Method	6/07	x		x				x	x	x	
Vis:Developing Assays and Graphing Data	6/07	x	x	x							x
Vis:Logs and pH	6/07	x	x		x	x					x
Stat: Bar Charts and Standard Error	6/07	x		x				x	x	x	
Vis: Log Transformations	6/07	x	x	x	x	x					
Vis:Calculating Molecular Weight	6/07	x									
Prob: BLAST and combinatorics	6/07	x				x	x	x			
Vis: 3D Visualization and microscopes	6/07	x				x					
Introductory Biology: Evolution and Ecology											
Prob: Basic Rules of Prob	9/06	x	x					x			
Prob: Intro to Punnett squares	9/06	x						x		x	
Stat: Testing differences with the T-Test	9/05	x		x					x		
Stat: Testing goodness of fit with the Chi-Square	9/06	x							x	x	
Dynamics: Exponential Growth and Decay	2/09	x	x	x	x					x	x
Introductory Biology: Organismal Biology											
Diffusion: The Introduction	2/05	x	x	x	x					x	x
Diffusion: Across Membranes	2/05	x	x	x						x	x
Diffusion: Osmosis	2/05	x	x							x	x
Diffusion: The Nernst Potential	9/05	x	x	x		x				x	x
Vis: Allometry	2/05	x	x	x	x	x					
Principles of Genetics											
Stat: Simulating goodness of fit	9/06	x		x				x	x		
Prob: Advanced Punnett squares	2/09	x		x				x	x	x	
Prob: Linked Genes and Recombination	9/06	x	x	x				x	x	x	
Dynamics: The Hardy-Weinberg Equilibrium	9/06	x	x	x	x			x	x	x	x
Microbiology											
Dynamics: Nonlinear Growth Rates	9/07	x	x	x	x	x				x	x
Dynamics: Stage-based Models	2/09	x	x	x	x					x	x
Dynamics: Enzyme Kinetics	2/09	x	x	x	x					x	x

The 26 currently developed modules and the metaskills and concepts focused on in each. KEY: Vis = data visualization; Stat = statistics; Prob = probability; Dynamics = population dynamics models; Diffusion = diffusion models.

Mice With Fangs," used in BSCI 106 (Introductory Biology: Evolution and Ecology). This module focuses on three of our metaconcepts: probability (making simple probability calculations and understanding the role of stochasticity), use of graphs (as an alternative way of visualizing probabilistic outcomes), and distilling biology into mathematical terms (parsing a verbal description into a probability calculation).

Figure 1 illustrates the organizational scheme common to all the modules, i.e., review of existing knowledge, development of new concepts, and applications of the new concepts. (Only a half of the table of contents is shown in Figure 1; in the remaining screenshots, we omit the table of contents to save space.) This screen also introduces a central metaphor used during the modules (comparing the choice of alleles to the flip of a coin) and the main characters in the module's storyline (mice with and without fangs).

FIGURE 1

Sample screenshot: Module organization. (Only half of the table of contents is shown.)

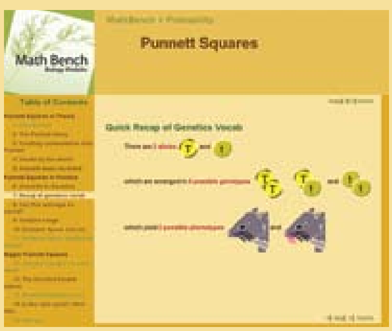


Figure 2 shows the beginning of concept development. This module is concerned with Punnett squares as a way of visualizing allele combinations. We begin the discussion of combination by introducing a nonmathematical situation: combinations of adjectives and nouns to create insults. This humorous introduction is meant to reduce students' anxiety about memorizing the "right way" to do a Punnett square and help them think intuitively about the logic of combinations.

FIGURE 2

Sample screenshot: Beginning of concept development (nonbiological example).

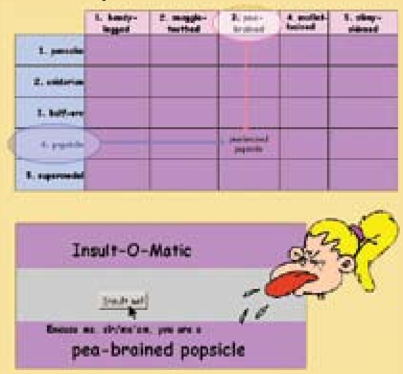


Figure 3 shows an example of an interactive applet that helps students master a technique, such as setting up a Punnett square. Students can check their answers along the way using the "Check Dad" and "Check Mom" buttons. Intelligent feedback is provided to help students understand their mistakes and find the correct answer. As in many MathBench applets, we reduce the busywork by allowing students to click on a button that fills in the remaining cells once they have correctly filled in the more difficult areas of the table. Finally, the applet allows open-ended practice for those who want it through the "New Problem" button.

The screen shown in Figure 4 extends students' understanding of the Punnett square by introducing stochasticity (1 of our 10 metacon-

FIGURE 3

Sample screenshot: The interactive Punnett square.

cepts). The preceding screens have led students through the prediction of a 9:3:3:1 ratio of phenotypes for a dihybrid cross. This section then begins by asking whether the expected ratio should be exactly reproduced in real-life situations. By running the applet several times, students can get a feel for the range of outcomes that are likely to occur, as well as observe another way to visualize the frequency data.

Students respond to the modules

We administered surveys electronically at the end of each of the first two modules (Introduction to Probability and Advanced Punnett Squares) in Principles of Genetics, a sophomore-level course required of all biological sciences majors and frequently taken by nonmajors interested in medical careers. The course covers principles and mechanisms of heredity and gene expression in plants, animals, and microorganisms. Enrollment was 351 students in two parallel sections that met twice weekly for lectures and once weekly in small (~20 students) discussion sections. The course demographics included 20% sophomores, 55% juniors, 22% seniors, and a few freshmen. Fifty-eight percent of students were female, and 78% had majors from within the College of Chemical and Life Sciences. For this group of students the average score in the math section of the Scholastic Aptitude Test (SAT) was 654.4 (standard deviation 78.6). At this point in their degree programs, most students (95%) are concurrently enrolled in or have completed a second semester of calculus, but anecdotal evidence from instructors suggests that students do not readily see the application of higher-level math to their biology courses. The sample size for students completing the survey was $n = 186$ for the probability module, and $n = 153$ for the Punnett square module.

After students completed each of the first two modules, we asked for open-ended feedback on whether they found the modules helpful, clear, and interesting. We read and coded the responses as 1 (negative), 3 (neutral), or 5 (positive) on four criteria: usefulness, clarity, interest, and examples. Samples of comments coded as positive include "It was really entertaining" (coded 5 for interest) and, "I thought it was helpful by providing many examples" (coded 5 for helpfulness and examples). Comments such as "I think the module was a little confusing but good overall" or "This module was OK" were coded as neutral, and comments such as "I did not enjoy this module, it was confusing to me" were coded as negative. Most students addressed only a subset of the criteria; we coded for a criterion only when a student addressed it directly. We also created a composite rating for each student by averaging the ratings for as many of the four criteria as that student addressed. The original coding was done by the first author, with cross-validation by a science education specialist. We also solicited open-ended feedback from the instructor of the course.

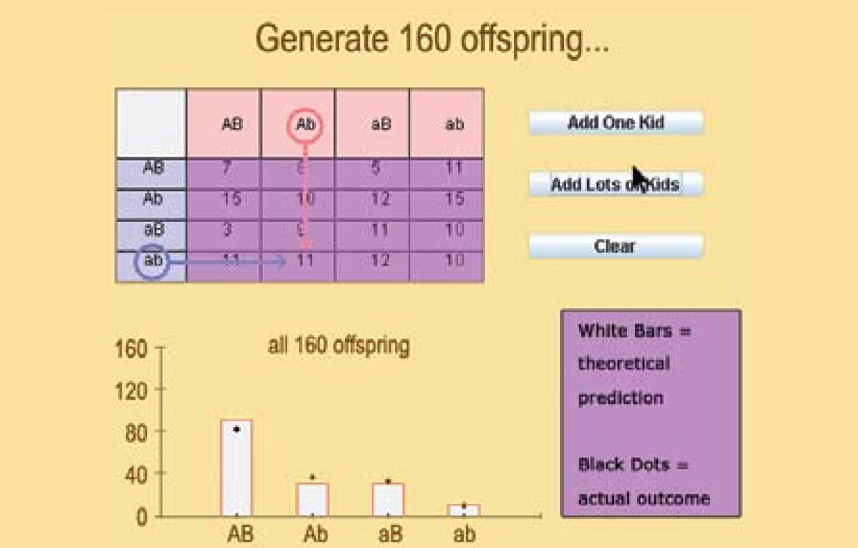
The average composite rating was 4.69 (out of 5) for the probability module and 4.51 for the Punnett square module. Individual criteria ratings ranged from 4.40 for clarity to 4.93 for interest on the probability module and from 4.51 for clarity to 4.63 for interest on the Punnett square module.

Dealing with math anxiety

Contrary to our expectations, only a few students felt that math was difficult for them prior to encountering the MathBench modules. This was surprising to us, given instructors' perceptions and prior experiences with undergraduate students. Nevertheless, students were appreciative of the informal style of the modules. Several students compared the mod-

FIGURE 4

Sample screenshot: Comparing a simulated outcome to the theoretical prediction.



ules favorably with their textbook ("The textbook is very thick on information and the tutorial is straight to the point. I liked being able to do an example and check whether I was right or wrong," and "It was so funny, so it let me understand so much more than trying to read the book"). While 6% of students said that the modules were too "wordy," most of this 6% gave the modules otherwise good reviews. Less than 5% of students felt that reading the textbook was a faster and/or clearer way to gain the same understanding.

A few students mentioned the use of fictitious traits specifically, and opinion was mixed on their usefulness, from comments such as "Real life organisms would be easier…to comprehend" to "Using fictional traits also made it easier but I'm not sure why." One student wrote, "One thing I liked was the inclusion of [J.R.R. Tolkien's] orcs in this module, because I feel orcs are a much underrepresented species in the world of biology."

The use of technology for interactivity

Most students reacted positively to the use of computer modules. Of the students who directly compared the modules and the textbook, 55% said they complemented each other well, 39% preferred the modules, and 6% preferred the textbook. Students who preferred the modules said that they were easier to understand or treated subjects with more depth, or that the interactive simulations and feedback contributed to their understanding. More specifically, 83% of students had positive reactions to the use of the interactive applet that allowed them to experiment with the Punnett square ("Having the interactive Punnett square helped give me confidence in my skills" and "The interactive Punnett squares were awesome! I was so glad to see that I didn't have to get out a piece of scratch paper to work those awful things out!"). Six percent of students disagreed, saying they would prefer to work without a computer ("The interactive Punnett squares were cool, but so annoying to do on a computer—way easier to write them out by hand!").

Student response to the modules was clearly affected by their learning preferences. Three students mentioned that the modules were especially useful to them because they were visual learners ("The interactive Punnett squares were particularly helpful, especially for visual learners like myself"). On the other hand, about 5% of students indicated that they were not attuned to working on a computer and therefore disliked the mode of delivery ("It was very clear but it is hard to just point-blank remember something from a screen," and "I feel that we are replacing the professor's lectures with the use of modules, and a professor who is there to answer questions while addressing the material is a much more adequate way of teaching any concept").

Learner control versus program control

It was clear that students enter Principles of Genetics with a very wide range of experience, and the time they reported investing in the modules varied widely, from five minutes to roughly three hours per module. Students did show that they were exercising learner control by speeding up or slowing down, depending on their needs: Sixteen percent said that the module was review for them and that they felt confident enough to work through it quickly. For example, one student wrote, "Took about 15 minutes…much better to do through a module than in class time, so we could go at our own pace." Other students appreciated being able to take their time ("It took me a bit under 2 hours… it made me feel relaxed while learning" and "[The module] really helped me a lot since…a lot of practice makes me get what I am studying").

Instructor's feedback

The instructor's feedback for the course echoed many of the student comments:

"In the time that we have been using these modules, I have gotten much positive feedback from my students. Many have commented on how the modules were written in such a way that it encouraged them to want to do them. They enjoyed the humor and math-friendly style. One student told me that she and her 'study-buddy' understood probability for the first time after working through the module—and it was because the stories in the module made it fun, not work. I have found that many of the students go back over the modules time and time again, to learn at their own pace… Those…at ease with math move quickly, and those with more anxiety move at a level that gives them more comfort."

Future plans

Based on the comments we received from students, we are planning a number of revisions to the modules. We are increasing the level of interactivity of all the modules, and in particular the amount and specificity of interactive feedback that students get when they make errors. We plan to help students determine how much effort they need to put into the modules by providing an ungraded diagnostic prequiz for each module. This quiz will tell students which parts of the module they need to focus on and which parts they can safely skip or skim. We will also make the modules more flexible by creating more randomly generated or database problems, which will allow students who want more practice to continue doing new problems until they feel comfortable with a topic.

We have also begun adapting the modules to allow for wider dissemination. Our student population is quite heterogeneous and many students transfer here from institutions that have not provided strong preparation in math. Because the modules are freely accessible online, they can help us coordinate our introductory curriculum with the community colleges that provide us with large numbers of students. Students transferring to the University of Maryland from these community colleges will have the opportunity to work with the same instructional materials as our native freshmen, which will help prepare them better for the more advanced coursework they need to complete their degrees. This collaboration with our local community colleges will eventually also allow us to evaluate the modules across a broader range of institutions.

Availability

The MathBench Biology Modules are freely accessible on the internet at *www.mathbench.umd.edu*. The modules require that students have JavaScript turned on and (for modules currently under revision or development) a Flash plug-in installed. We have found that these requirements do not pose problems for students, as both JavaScript and Flash are already widely used. We invite biology instructors to use the modules in their classes and welcome feedback and suggestions based on their experiences. To request assistance with using the modules or offer feedback, please contact the first author at *kanelson@umd.edu.* ■

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References

American Association for the Advancement of Science (AAAS). 1993. *Benchmarks for science literacy.* New York: Oxford University Press.

Bahrick, H.P., and L.K. Hall. 1991. Lifetime maintenance of high school mathematics content. *Journal of Experimental Psychology: General* 120 (1): 20–33.

Berger, C. 1984. Learning more than facts: Microcomputer simulations in the science classroom. In *Intelligent schoolhouse: Readings on computers and learning,* ed. D. Peterson. Reston, VA: Reston Publishing.

Betz, N.E. 1978. Prevalence, distribution, and correlates of math anxiety in college students. *Journal of Counseling Psychology* 25 (5): 441–48.

d'Ailly, H.H., J. Simpson, and G.E. MacKinnon. 1997. Where should "you" go in a math compare problem? *Journal of Educational Psychology* 89: 562–67.

Ellis, J.D. 1984. A rationale for using computers in science education. *American Biology Teacher* 46 (4): 200–206.

Ewing, J. 2002. The next big thing in mathematics. *Chronicle of Higher Education.* Sept. 20.

Gross, L. 1994. Quantitative training for life-science students. *BioScience* 44 (2): 59.

Gross, L. 2000. Education for a biocomplex future. *Science* 28: 807.

Hannafin, R.D., and H.J. Sullivan. 1996. Preferences and learner control over amount of instruction. *Journal of Educational Psychology* 88 (1): 162–173.

Hastings, A., and M.A. Palmer. 2003. Mathematics and biology: A bright future for biologists and mathematicians? *Science* 299: 5615.

Jungck, J.R. 2005. Challenges, connection, complexities: Educating for collaboration. In *Math & bio 2010: Linking undergraduate disciplines,* ed. L.A. Steen. Washington DC: Mathematical Association of America.

Mayer, R.E. 2002. Rote versus meaningful learning. *Theory Into Practice* 41 (4): 226–32.

Mayer, R.E., S. Fennell, L. Farmer, and J. Campbell. 2004. A personalization effect in multimedia learning: Students learn better when words are in conversational style rather than formal style. *Journal of Educational Psychology* 96 (2): 389–95.

National Research Council (NRC). 2003. *Bio2010: Transforming undergraduate education for future research biologists.* Washington, DC: National Academies Press.

Reed, S.K. 1985. Effect of computer graphics on improving estimates to algebra word problems. *Journal of Educational Psychology* 77 (3): 285–98.

Ross, S.M, and P. Anand. 1987. A computer-based strategy for personalizing verbal problems in teaching mathematics. *Educational Communication and Technology Journal* 35: 151–62.

Steen, L.A. 2005. The "gift" of mathematics in the era of biology. In *Math & bio 2010: Linking undergraduate disciplines,* ed. L.A. Steen. Washington, DC: Mathematical Association of America.

Tversky, B., J.B. Morrison, and M. Betrancourt. 2002. Animation: Can it facilitate? *International Journal of Human-Computer Studies* 57: 247–62.

Wender, K.F., and J. Muehlboeck. 2003. Animated diagrams in teaching statistics. *Behavior Research Methods, Instruments, and Computers* 35 (2): 255–58.

Yuan, R. 2005. A quantitative approach to the biology curriculum: Issues to consider. In *Math & bio 2010: Linking undergraduate disciplines,* ed. L.A. Steen. Washington DC: Mathematical Association of America.

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