EOS
EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 89 NUMBER 16
15 APRIL 2008
PAGES 149–160

Making Undergraduate Geoscience Quantitative

PAGES 149–150

Modern geoscience uses equations, models, and numbers in conjunction with observations, maps, and words as fundamental tools for investigating Earth. Yet the U.S. public persists in viewing the study of Earth processes as highly qualitative and, in many states, as a remedial science course that is not accepted as appropriate preparation for admission to U.S. colleges and universities. Geoscience teachers and faculty are working to change this perception by increasing the quantitative content of the geoscience curriculum.

From the most mathematical of senior theses to the most basic of introductory courses, geoscience instructors can make these courses more reflective of the full range of tools used in the geosciences by including the quantitative content and methods that pervade geoscience. In addition to being provided with a more realistic perception of our science, college students whose major study is the Earth sciences will be better prepared for geoscience careers and all of our students will be more quantitatively literate.

Geoscience majors, the geoscience workforce of tomorrow, need to be prepared to meet the quantitative demands of industry, research, and education. In 2006, a group of 20 U.S. graduate and undergraduate faculty and graduate students convened at Carleton College, in Northfield, Minn., to discuss the quantitative preparation of future geoscience graduate students (http://serc.carleton.edu/12980). Participants concluded that (1) the development of quantitative skills lags well behind other core geoscience skills (geologic interpretation, historical analysis, visualization, data collection, and communication) and (2) many undergraduate geoscience majors, even those exposed to quantitative material, generally lack the ability to apply quantitative skills to geoscience problems. As a result, this group perceived a shortage of graduates who have strong backgrounds in both geoscience and quantitative analysis. Similar concern has been expressed by members of industry [*Loudin*, 2004].

Quantitative literacy, or numeracy—the ability to use and understand quantitative information in everyday life—is essential for citizens in a world that bombards us with numbers on a daily basis [*Steen*, 2001]. Because geoscience is perceived by many students as an "easy" science, our introductory college courses often draw students who seek to avoid quantitative problem solving. Introductory geoscience courses that use quantitative approaches can help students to develop quantitative literacy. In contrast, omission of the quantitative aspects of our science in introductory courses reinforces the notion that quantitative reasoning is not something that citizens need every day.

Building quantitative information into any geoscience course can be challenging. Over the past 5 years, the U.S. National Science Foundation (NSF) has funded a series of workshops (including the meeting described above) to help geoscience faculty teach more quantitatively. Critical aspects of workshop discussions included identifying skills that students need to succeed with quantitative geoscience concepts, developing strategies for teaching quantitatively, and considering the role of geoscience departments in increasing the quantitative content of the curriculum. As a starting point for a larger community discussion, below we present major lessons learned through the workshop series.

What Skills Do Our Students Need?

If our goal is both to teach geoscience in ways that demonstrate its quantitative nature and to improve our students' quantitative skills, we as instructors need to articulate the skills that we want them to develop and use. Although one might expect that this list depends on geologic topic or student/faculty expertise, we found that when faculty are asked to identify specific skills needed by geoscience students, there is more agreement than dissent. First and foremost, faculty are concerned that

Geoscience provides abundant opportunities to engage students with multiple representations of quantitative teaching. In this picture, students at Hamilton College, in Clinton, N.Y., work on a map of Egypt. Photo courtesy of Dave Tewksbury.

By C. A. Manduca, E. Baer, G. Hancock, R. H. Macdonald, S. Patterson, M. Savina, and J. Wenner

students learn to use quantitative approaches to solving problems, particularly real problems related to their everyday lives and geologic problems for those who continue as geoscience majors.

When asked what specific skills are important for geoscience majors, there is strong agreement that the core includes basic arithmetic, algebra, and statistics; the ability to use equations and models to describe natural processes; estimation and back-of-the-envelope calculations; and modeling and understanding uncertainty.

Thinking more specifically about students going on to graduate school, the graduate faculty, undergraduate faculty, and graduate students who met in 2006 offer this list of important skills for geoscience majors:

Basics: graphing, unit conversion, dimensional analysis, estimation, substitution of variables, and solving systems of equations;

Functions: dependent and independent variables, separation of variables, types of functions (linear, power, exponential, logarithmic), and periodic functions;

Multivariable analysis: trigonometry, vectors, directional derivatives, gradient, slope, matrices, linear algebra, and sensitivity analysis;

Statistics and probability: descriptive statistics and error analysis (mean, median, standard deviation, confidence interval), regression analysis, conditional probability, accuracy analysis, and probability distributions;

Calculus: ratio, rate, sum and integral, and derivative and partial derivative.

These suggestions for skills central to the undergraduate major and to graduate preparation are offered as a starting point for broader discussion. While there is no need for a national consensus on exactly what skills are critical, we found that articulating skills facilitated the discussion of methods, courses, and curriculum within our workshops and our departments.

Strategies for Successful Quantitative Teaching

The wide range of preparation, comfort with, and interest in quantitative approaches on the part of both faculty and students can present many challenges to teaching quantitative geoscience. One outcome of the workshop series is a collection of online resources designed to help faculty teach geoscience more quantitatively (http://serc.carleton.edu/quantskills). This collection includes discussions of teaching techniques (e.g., back-of-the-envelope calculations, quantitative writing assignments, teaching with equations) and numerous examples of quantitative activities and assignments for use in introductory and upper division courses.

Assembling the expertise of geoscientists and mathematicians to understand effective strategies for teaching mathematical skills in a geoscience context was fundamental to developing these resources. Here we present four strategies emerging from these discussions. These four strategies can be helpful for teaching activities ranging from a simple presentation of data in a lecture to the design of a full course or curriculum.

Represent the same information in different ways. Quantitative information can be presented using descriptive, symbolic, and graphical presentations. Presenting students with multiple representations of the same data recognizes different learning styles and allows a student several possible ways to connect initially with the information. A strong understanding of how the representations are related increases the robustness of students' understanding and their ability to transfer this learning to new situations [*Pape and Tchoshanov*, 2001]. Technology offers many new opportunities to visualize and manipulate data that can help students make connections between different representations. For example, many faculty now use spreadsheets to allow students to plot and manipulate the output of equations describing geologic processes. Bill Locke at Montana State University has used this approach in teaching geomorphology with a series of Excel models addressing slope and scarp formation, stream equilibrium, and glacial flow lines (http://serc.carleton.edu/10528).

Work in groups. Group work supports student development of quantitative skills on several levels [*Davidson and Kroll*, 1991]. Students in groups have opportunities to verbalize their quantitative thinking and to share and defend the logic involved in quantitative problem solving. Groups also provide important social support for quantitative learning and may lead to exploration of alternative approaches to problem solving. Group projects can last from minutes to months. Students in a large class can be asked during a lecture to take a few minutes to strategize with their neighbors to solve a short problem or interpret a graph. For example, Bill Prothero at the University of California, Santa Barbara (http://serc.carleton.edu/3815) asks students to compute the time it takes 14-second-period waves to travel across the Pacific Ocean. On a longer timescale, students in a laboratory class can work in groups across multiple class periods to develop a quantitative model of the carbon cycle using a commercial modeling program like the STELLA™ program [*Bice*, 2006].

Provide opportunities for practice and reflection. The use of activities that extend across multiple days and revisit the same skills in multiple contexts throughout the duration of a college course or major concentration can help students reflect on, synthesize, and internalize quantitative skills. This is essential to developing proficiency with quantitative skills and the ability to apply skills in new situations [*Edelson*, 2001]. For example, the Spreadsheets Across the Curriculum project (http://serc.carleton.edu/20801) provides a series of activities that use spreadsheets repeatedly over several weeks to help students understand topics such as density and earthquake magnitude through equations and graphs.

Teach the full set of problem-solving skills. Mathematicians have given much attention to teaching problem solving [*Schoenfeld*, 1992]. In addition to scientific understanding and quantitative skills, this research highlights the importance of (1) developing students' ability to self-monitor progress on a problem and (2) instilling a new set of beliefs that support problem solving. Self-monitoring of learning, or metacognition, is known to characterize experts in a field and can be explicitly taught [*National Research Council*, 2000]. For example, a series of questions incorporated into an activity can focus students' attention on the decisions they make in solving the problem: How did they begin to attack the problem? When did they switch approaches? How could they tell if a strategy was working? Students, especially those less confident in their quantitative skills, may hold beliefs such as "only experts can solve problems" or "there is only one way to solve a problem." Acknowledging the importance of beliefs in supporting or hindering problem solving is the first step toward recognizing those beliefs as barriers to learning and devising strategies for changing them.

The Teaching Quantitative Skills in the Geosciences Web site provides examples of ways in which each of these strategies can be used to address specific quantitative skills in different geoscience contexts (http://serc.carleton.edu/8923). For example, students often struggle with logarithms, which occur repeatedly in geoscience topics throughout the geoscience curriculum, including introductory geoscience courses. In addition to providing examples of multiple ways of representing and presenting logarithms, we describe several introductory-level activities that use logarithms to estimate earthquake probability and recurrence interval, to develop a scale model of the solar system, and to understand floods.

Critical to any teaching activity are the assessments that allow faculty to evaluate if the desired student learning is taking place. Quantitative learning can be assessed using strategies that range from evaluating quantitative arguments in writing assignments [*Lutsky and Bierman*, 2006] to analyzing students' problem-solving notes [*Heller*, 2006] to using traditional problem sets and tests. A full discussion of assessment techniques and their use in geoscience courses has been developed by the On the Cutting Edge professional development program (http://serc.carleton.edu/9142). Combining careful initial design of the activity prior to implementation with assessments to understand its impact puts faculty members in a powerful position to improve activities and assignments so that they can help students develop quantitative reasoning abilities.

Working as a Department to Build a Quantitative Program

As members of a larger college or university community, we are commonly concerned that increasing the quantitative component of geoscience courses will result in decreasing enrollments—that students will opt for less quantitative introductory electives. This concern can be partially addressed when members of a geoscience department work together to change faculty and student attitudes. Quantitative skills must be viewed not as optional but as central to our understanding of Earth processes. Beginning with introductory courses, quantitative approaches infused throughout the curriculum can lead to changes in student attitudes about quantitative skills, leading many students to develop the habit of using quantitative reasoning and strong quantitative competency.

A department may wish to start with a conversation that defines the department's goals for students' quantitative learning. These goals can then be both used as a faculty planning tool and shared with students to help them understand the importance the department places on quantitative reasoning. Using these goals and the courses in the major, a matrix can be created to illuminate where students engage in experiences that address each goal [*Macdonald and Bailey*, 2000]. This matrix can be used to articulate connections between courses for students or to identify holes in the cumulative student experience. It can also be helpful in identifying different places in which students are first introduced to tools (such as Excel, STELLA™, or MatLab) that are used repeatedly in a curriculum.

Providing support for students who find quantitative work difficult may be a major challenge for a department. In addition to thinking carefully about the design of quantitative activities and assignments, several institutions have experimented with formal support structures. West Chester University of Pennsylvania offers a shadow course associated with calculus instruction where students solve geoscience problems using the calculus concepts being taught in the primary course [*Lutz and Srogi*, 2000]. A significant outcome has been a positive shift in students' attitudes toward mathematics. Highline Community College, in Des Moines, Wash., has used the inverse approach, where a shadow course offering "just in time" help with math skills is offered in conjunction with an introductory geoscience course. Geoscience faculty at other colleges and universities have provided geoscience examples for use by mathematics or physics faculty. On-campus and online centers for math skills offer another source of support for students (e.g., http://serc.carleton.edu/9529).

Working Together as a Community

Infusing quantitative skills into our courses is essential to improving the quantitative literacy of our citizens and to creating a geoscience workforce with appropriate quantitative skills. While not an easy task, we can better succeed if we act as a community, rather than as individuals in isolation.

Workshop participants have suggested that as a community, we could do the following:

- share our successes in the classroom through informal discussions with our colleagues, formal workshops, and the Teaching Quantitative Skills in the Geosciences Web site (http://serc.carleton.edu/4242). Talking about our teaching and documenting successful teaching materials so that others can use them improves our individual teaching and raises the level of expertise across the community;
- collaborate with the mathematics community, on campus or through workshops, to provide experiences for students that build on the expertise in the mathematics and geoscience communities and better integrate instruction in both subjects; and
- value and reward efforts to develop curricula that are quantitatively rich.

Moving Forward

Geoscience is quantitative. For many of us, the excitement of applying quantitative techniques to understanding aspects of the Earth system was a major motivation for entering the geosciences. Bringing quantitative approaches into our teaching is an opportunity to share that excitement and to raise awareness of the power our science brings to addressing many of the major societal issues of our time. You can begin today by infusing just one more quantitative activity into your course or by initiating a conversation with your department.

For more resources or to join the quantitative skills online discussion, visit http://serc.carleton.edu/quantskills.

Acknowledgment

This work was funded by NSF grant 0085600. Any opinions, findings, conclusions, or recommendations expressed in this article are those of the authors and do not necessarily reflect the views of NSF.

References

Bice, D. M. (2006), STELLA modeling as a tool for understanding the dynamics of Earth systems, in *Earth and Mind: How Geologists Think and Learn About the Earth*, *GSA Spec. Pap. 413*, edited by C. A. Manduca and D. W. Mogk, pp. 171–185, Geol. Soc. of Am., Boulder, Colo.

Davidson, N., and D. L. Kroll (1991), An overview of research on cooperative learning related to mathematics, *J. Res. Math. Educ.*, *22*(5), 362.

Edelson, D. (2001), Learning for use: A framework for the design of technology-supported inquiry activities, *J. Res. Sci. Teach.*, *38*(3), 355–385.

Heller, K. (2006), Teaching problem solving in large introductory classes: The view from physics, paper presented at the Infusing Quantitative Literacy Into Introductory Geoscience Courses workshop, Natl. Assoc. of Geosci. Teachers, Northfield, Minn., 26–28 June. (Available at http://serc.carleton.edu/quantskills/workshop06/index.html)

Loudin, M. (2004), Where in the world will we find our future geoscientists? One employer's perspective, *Eos Trans. AGU*, *85*(47), Fall Meet. Suppl., Abstract ED31B-0748.

Lutsky, N., and S. Bierman (2006), Quirks of rhetoric: A quantitative analysis of quantitative reasoning in student writing, paper presented at 2006 Joint Statistical Meetings: Statistics for an Uncertain World—Meeting Global Challenges, Am. Stat. Assoc., Seattle, Wash., 6–10 Aug. (Available at http://www.amstat.org/meetings/jsm/2006/onlineprogram/index.cfm?fuseaction=abstract_details&abstractid=306686)

Lutz, T. M., and L. Srogi (2000), The role of a shadow course in improving the mathematics skills of geoscience majors, *J. Geosci. Educ.*, *48*(4), 474. (Available at http://www.nagt.org/nagt/jge/sept_2000.html#v48p474)

Macdonald, R. H., and C. M. Bailey (2000), Integrating the teaching of quantitative skills across the geology curriculum in a department, *J. Geosci. Educ.*, *48*(4), 482–486. (Available at http://www.nagt.org/nagt/jge/sept_2000.html#v48p474)

National Research Council (2000), *How People Learn: Brain, Mind, Experience, and School*, Natl. Acad. Press, Washington, D. C.

Pape, S. J., and M. A. Tchoshanov (2001), The role of representation(s) in developing mathematical understanding, *Theory Into Practice*, *40*(2), 118–127.

Schoenfeld, A. (1992), Learning to think mathematically: Problem solving, metacognition, and making sense in mathematics, in *Handbook of Research in Mathematics Teaching and Learning*, edited by D. A. Grouws, pp. 334–370, Macmillan, New York.

Steen, L. A. (Ed.) (2001), *Mathematics and Democracy: The Case for Quantitative Literacy*, 121 pp., Woodrow Wilson Natl. Fellowship Found., New York.

Author Information

Cathryn A. Manduca, Science Education Resource Center, Carleton College, Northfield, Minn.; E-mail: cmanduca@carleton.edu; Eric Baer, Geology Department, Highline Community College, Des Moines, Wash.; Greg Hancock and R. Heather Macdonald, Department of Geology, College of William and Mary, Williamsburg, Va.; Sam Patterson, Department of Mathematics, Carleton College; Mary Savina, Department of Geology, Carleton College; and Jennifer Wenner, Department of Geology, University of Wisconsin-Oshkosh