Integrating the Teaching of Quantitative Skills Across the Geology Curriculum in a Department

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ABSTRACT

One approach to teaching quantitative skills to all students in a department is to construct a matrix of the desired quantitative skills versus courses in the departmental curriculum. Faculty members complete the matrix by listing the assignments in each course that build each particular skill and then design activities or assignments that either fill a gap or more fully develop a skill or application. Faculty members discuss the matrix on a regular basis to report progress and challenges, share ideas with each other, and plan future directions. This iterative process enhances the quantitative skills of students by incorporating quantitative activities and problems throughout the geoscience curriculum. When some quantitative work is included in every departmental course, students recognize that quantitative tools are important in the geosciences. Communication, cooperation, and planning at the department level and regular reviews of the matrix are key aspects for developing quantitative skills across the departmental curriculum.

Keywords: Education – geoscience; education – undergraduate; geology – teaching and curriculum; miscellaneous and mathematical geology.

Introduction

The geosciences have changed in the last century from being dominantly descriptive to being more quantitative, and the undergraduate geoscience curriculum at some institutions reflects that change. For example, the revised curriculum at the University of Minnesota uses mathematics and basic sciences throughout the curriculum and includes mathematics and computational experiences from the beginning (Paola and others, 1995). However, many geoscience courses, particularly those at the entry level, are presented as being almost completely non-quantitative. In addition, developing the quantitative skills of undergraduate students – majors as well as non-majors – is not an explicit goal of many geoscience departments. We argue that developing the quantitative skills of all students who take geoscience courses should be an important goal, consistent with recommendations given in *Shaping the Future of Earth Science Education* (Ireton and others, 1996) to integrate and incorporate quantitative reasoning across the curriculum.

Departments interested in building the quantitative skills of their students have taken various courses of action. Some departments already have a strong sequence of courses in which such skills are developed; this may be the result of curricular reform (for example, at the University of Minnesota, Paola and others, 1995) or some other cause. Other departments offer a specific course that focuses on mathematical approaches to geologic problem solving and computational geology (for example, see Vacher, 2000, this issue). Some departments teach a shadow course – a course in geology taken concurrently with a calculus course – as described by Lutz and Srogi (2000, this issue). In some departments, a focus on student research in courses throughout the curriculum develops the quantitative skills of undergraduate majors (for example, see Keller and others, 2000, this issue). We suspect that in many departments, some courses are quantitative and others are not, reflecting either the preference of individual faculty members or a conscious departmental decision. Our department uses a cooperative, iterative approach, which we call the matrix approach, to systematically develop the quantitative skills of majors and non-majors across the geoscience curriculum.

In this paper, we briefly describe the departmental context and our approach to developing skills across the departmental curriculum. We then illustrate the results of the matrix approach by describing its use in entry-level courses and discussing one quantitative component applied across the departmental curriculum. We also identify critical aspects for others who might want to use a similar approach.

The Matrix Approach to Building Quantitative Skills across the Curriculum

The Department of Geology at the College of William and Mary is an undergraduate program that graduates between 15 and 25 majors a year and includes five faculty members and one instructor who coordinates the introductory laboratories. We teach a range of introductory courses from small freshman seminars (15 students) to large lecture classes (100-170 students). Majors take a sequence of eight core courses with two electives and one year of chemistry; many also take calculus and physics. All William and Mary geology majors complete a year-long senior research project.

As a result of a number of factors, including recent departmental assessments and the addition of new faculty members, the department has begun a process of articulating and reviewing the goals we have for our students in terms of the geological reasoning and other skills we want them to develop. We identified quantitative-skills development as a critically

Quantitative Component	Physical Geology, Geography	Historical Geology	Mineralogy	Petrology	Sed/Strat	Surficial Processes	Paleontology	Structural Geology
Estimating	medium	light	light	light	medium	medium	light	medium
Measuring	light	medium	medium	medium	medium	medium	heavy	heavy
Determining rates	heavy	medium	light	light	medium	heavy	medium	medium
Graphing	medium	light	medium	heavy	light	medium	medium	heavy
Modeling	light	light	medium	medium	light	heavy	light	medium
Geochronology	medium	medium	light	light	medium	heavy	light	heavy
Statistics	light	light	light	medium	medium	medium	heavy	medium

Table 1. Matrix of quantitative components versus core curriculum courses with light, medium, and heavy reflecting the emphasis of particular component in a specific course.

important goal because many geologic problems require quantitative solutions, many graduate schools and employers expect new employees to have a significant level of quantitative proficiency, and the newer faculty are involved in research that is quantitative. In addition, introductory natural-science courses at William and Mary that meet the new general education requirements (implemented in 1995) are expected to address the role of mathematics in science, providing additional incentive to make such courses more quantitative.

Our approach is to identify the quantitative components (skills and applications) that we want students to develop in our courses and then to construct a matrix of the components versus courses in the departmental curriculum. Our approach is adapted from the "spreadsheet" approach used by Mary Savina (personal communication, 1995) in the Geology Department at Carleton College. This approach requires that all faculty members in a department work together to develop and periodically review the matrix. We followed the steps listed below to integrate the teaching of quantitative skills throughout the curriculum.

1) Discuss the quantitative components that are important for geoscience students to develop. Identify those particular skills and applications that should be addressed throughout the curriculum, including entry-level courses.
2) Collectively determine the emphasis (heavy, medium, or light) each component should have in each course and specify the appropriate type of mathematics needed (for example, algebra, geometry, trigonometry, or calculus) for each component.
3) Consider the current assignments and activities in each course relative to the listed components and discuss whether to add assignments or activities, offering suggestions to colleagues about possible assignments or activities.
4) Each faculty member then develops or revises assignments or activities as needed. In some cases, a faculty member might teach other faculty members about a particular skill or application.
5) Assess progress, an important step we have not fully implemented. Periodically review and redo each of the previous steps (which we have done) and measure changes in student outcomes (which we have not yet formally done) in an iterative process. Use results of the assessment to revise assignments and refine the matrix.

The quantitative components we identified as most important include estimating, measuring, and determining rates of earth processes, modeling earth processes, doing geochronological calculations, and statistically analyzing data (Table 1). The list includes both specific skills and some more complex applications of quantitative skills needed for a better understanding of the geosciences. Estimation skills involve making simple observations about the distance, size, volume, rate, and so forth of earth materials and processes without the aid of equipment (for example, estimating the discharge of a stream). Measuring skills are similar to estimation skills, but require the use and manipulation of equipment (for example, flow meter and measuring tape used to determine stream discharge). Recognizing that rates of Earth processes occur over a broad temporal range, students should have the ability to both estimate and measure these rates. Examples include using real data to estimate and measure ground-water-flow velocities, erosion rates, weathering rates, and tectonic plate velocities. The geochronology component concerns determining the age of earth materials. We want students to understand the first principles, mathematics, specific systems, techniques, and limitations of geochronology. By determining the age of Earth materials, students can then calculate rates of certain Earth processes. Our list of quantitative topics is by no means comprehensive, although it might be useful for other departments.

Others who use the matrix approach might choose to list specific mathematical skills or particular levels of mathematics (for example, algebra or calculus). We did not list specific levels of mathematics because we did not view developing mathematical skills as the primary goal, rather we wanted students to use mathematics as a tool to help answer earth-science questions. Also, different levels of mathematics are used in different courses for the same quantitative component (for example, algebra is used with geochronology in introductory geology, whereas calculus is incorporated with geochronology in structural geology). Rather than teach trigonometry or calculus as specific topics in our courses, we bring them up when the need arises. Although not explicitly included in the matrix, we have also discussed how and where we apply mathematical techniques used in biology, chemistry, and physics to our geology courses.

The instructor decides the level at which each quantitative skill is covered in a particular course, with some feedback from the other faculty. Some courses lend themselves to substantial use of certain quantitative skills, whereas others do not. Light emphasis of a quantitative component in a course would typically mean students are given a brief introduction and overview in lecture and a few problems are solved using the skill. A course placing a heavy emphasis on a particular component would involve significant discussions in lecture and numerous problems about that topic on problem sets, laboratories, and examinations throughout the semester. In addition, we expect that students become "fluent" in that component, using the skills in a variety of ways and understanding the nuances of working with that component.

Results of the Matrix Approach

We first discussed improving our teaching of quantitative skills and developed the matrix in 1998. Since then, we have met to review the matrix and discuss progress once or twice a year in formal meetings. We informally talk with each other about various aspects of assignments and skills much more frequently. Each faculty member has developed new or revised assignments or activities that involve quantitative components. When faculty members articulate their goals for a particular course, list the quantitative skills students will use in that course, and discuss specific course activities and assignments, they learn from each other about successful classroom strategies as well as the difficulties associated with incorporating quantitative material. At William and Mary, such a coordinated effort has resulted in a more coherent program in which faculty know what to expect from students who have taken a certain set of courses and can use that knowledge to build upon the students' skills. Repetition, where present, is consciously used for reinforcement rather than being an inadvertent duplication of the same or similar problems or examples. This coordinated effort can also reveal gaps in a curriculum; we have realized that we need to be doing more in terms of modeling and statistics, including error analysis.

We give two examples that illustrate results of using the matrix approach – one focusing on entry-level courses in the department and the other on the thread of geochronology across the curriculum. Both examples show how cooperation can strengthen the curriculum and the development of students' quantitative skills, the first by producing a more common set of experiences and activities at the introductory level and the second by focusing, developing, and reinforcing a particular application as faculty members incorporate or modify assignments.

The Department of Geology offers different entry-level courses: two large, lecture-based courses (Physical Geology and Physical Geography) and small seminars for first-year students. A decade ago, the introductory courses were predominantly descriptive, students in different courses had different experiences, homework – when given – included short papers, problem sets were non-existent, and discussions among instructors about course content and instructional strategies were not common. We initially focused on skills in the large, lecture-based courses; these courses have an associated optional laboratory course that is taken by some, but not all, of the students in the lecture-based course. Faculty offer help sessions at regular intervals, in addition to office hours. Therefore, given our goal of developing the quantitative skills of all our students, we wanted to incorporate quantitative materials in the lecture-based course. Recognizing that each course is different and that each instructor focuses on different things and teaches differently, we still agreed to share ideas and pool resources.

Currently, all faculty teaching these introductory courses work numerical problems in class and give quantitative problem sets, so all students have similar experiences and cannot take a particular class to avoid this quantitative work. The faculty members share ideas about classroom activities and include some similar problems in the problem sets. We all include work on measuring and estimating, determining rates of processes, mass balances, fluxes, and geochronology. Table 2 lists some of the problems given to students in the introductory courses, and Bailey (2000a and this issue) gives more detailed examples of these problems. To help students with the quantitative work, faculty offer help sessions at regular intervals. To reduce the workload of the faculty members in large classes, we use geology majors as graders for some parts of the problem sets.

In our last review of the matrix, we decided that students need more written background material for some aspects of the quantitative components not included in the course textbooks. We are working together to put ancillary material such as background information, sample problems, and worked solutions on a website. This will ensure that faculty members use consistent terminology and symbols and that every student, regardless of course or instructor, will have a common base. These strategies are consistent with recommendations made by Shea (1990) that "a realistic and illustrative example should be worked completely and explained carefully. Several realistic problems of different degrees of difficulty should be provided."

The matrix approach also changed our teaching of geochronology. We decided that accurately determining the age of Earth materials should be one of the main threads across the curriculum and that students should learn about various methods of dating Earth materials. When we began our discussions about geochronology, we realized that some courses included a discussion of this quantitative component and others did not. In addition, we realized that the same isotopic systems were presented in more than one course. We now have a much more systematic introduction and development of this quantitative component throughout the curriculum. Some aspect of geochronology is included in every course, either for reinforcement of what had been done previously or

Component	Physical Geology, Physical Geography*	Structural Geology
Estimating	Distance, relief, stream discharge on campus, drainage basin area, percent of minerals in rock, daily water usage, residence time of water in campus pond	Force and stress on a surface and in the crust
Measuring	Size of minerals in rock, thickness of spalled flakes on limestone columns, stream discharge, discharge from water faucets, angle of repose/failure in earth materials, drainage basin area, latitude and longitude change from dorm room to classroom, density of rocks	Distance and angles with Brunton compass, orientation of rock structures with Brunton compass, strain in rocks
Determining rates	Stream velocities, ground-water velocities in Ogallala Aquifer and on campus, shoreline migration rates at the Outer Banks, North Carolina and Ocean City, Maryland, plate spreading rates, water usage, weathering rates, erosion rates in Himalayas and the Piedmont	Strain rates from experimental data, naturally deformed rocks, and lithospheric plates
Graphing	Stress vs. strain, isotope decay profile, daily and yearly temperature changes, personal water usage	Stress vs. strain, Mohr diagrams, stereograms
Modeling		Stress history of materials during burial, uplift, and tectonism, Experimental deformation with squeeze box
Geochronology	U-Pb, K-Ar, age of groundwater pumped from Ogallala Aquifer, age of volcanic and plutonic rocks, age of Antarctica ice cores, age of earth from salt in the sea (and why this method does not work),	U-Pb and concordia diagrams, Rb-Sr and isochron diagrams, Ar-Ar and plateau diagrams
Statistics		Error analysis from geochronology data and distance/angle measurements
*We include here the activities and assignments given the lecture-based courses; the laboratory is not required for students taking the courses.		

Table 2. Completed matrix of quantitative components versus courses for the entry-level courses (Physical Geology and Physical Geography) and Structural Geology. Not all activities listed in an entry-level rectangle are used in every entry-level course.

for introduction of new material. Students in all entry-level courses plot data and calculate the age of igneous rocks using parent/daughter ratios and decay constants. In all other courses, students build on this base in a way appropriate to the course subjects, learning about additional dating techniques and applying them in different situations. For example, students in Surficial Processes complete assignments on cosmogenic radionuclide dating techniques as well as carbon-14 data analysis, while students in Structural Geology calculate ages using U-Pb, Rb-Sr, and Ar-Ar techniques and discuss their significance as part of a semester-long project. Some problems can be solved algebraically using parent/daughter ratios and the decay equation, some problems require students to use data to produce and then interpret geochronology graphs (for example, concordia plots), and other problems require students to interpret and evaluate existing graphs. By the time they graduate, geology majors have used and manipulated geochronologic data in a variety of ways and know more about the different ways geoscientists can determine the age of various Earth materials.

Aspects Critical for Success

For the matrix approach to work effectively in a department, certain factors must be in place. First, faculty members in a department must agree that developing a particular skill or skills (in this case, quantitative skills) is an important goal and that each course will contribute to the development of student skills in this area. Second, faculty members must be willing to talk openly about what they do (and don't do) to help develop quantitative skills in each of their courses. They must be willing to share their assignments, to discuss the activities and approaches they use in the classroom, and to be candid about what works and what doesn't. Third, faculty must be willing to change what goes on in their courses and take suggestions and advice from other faculty, although individual faculty members retain ultimate control of their courses.

We have not formally assessed our progress, but our perception is that William and Mary geology students are becoming more adept at quantitative thinking. Several years ago, some students were quite hostile to quantitative work (based on student comments), whereas now such work is simply accepted. In fact, undergraduate majors seem to expect quantitative work in their geology courses. We also note that the percent of senior research projects that are quantitative has increased in recent years. During a three-year period (1996-98), approximately 40% of senior research projects (n = 61) included some quantitative treatment, and in the most recent three-year period (including current senior research projects), 75% of the senior research projects (n = 47) have had a significant quantitative component. This increase is most likely the result of the addition of faculty members who do quantitative research but is also an indication that students are choosing to conduct research that requires a quantitative understanding. We are convinced that the matrix approach has significantly improved our teaching of quantitative skills across the curriculum.

Since the time of our first discussion on this topic, we have identified other quantitative skills to add to the matrix. For example, we have not yet explicitly addressed how computing technology fits into the development of quantitative skills. We also have become aware of the work done by the mathematical community in developing its standards (AMATYC, 1995; NCTM, 2000) and the integration of mathematics and science articulated in the *National Science Education Standards* (NRC, 1996). Departments should consider using the standards given in these publications as a starting point for discussion of the skills and abilities they want their students to develop. In particular, we think it would be very useful to consider the standards articulated in *Crossroads in Mathematics: Standards for Introductory College Mathematics Before Calculus* (AMATYC, 1995), specifically the Standards for Intellectual Development, which address desired modes of student thinking, and the Standards for Content. Talking with colleagues in mathematics and mathematics education about how to best develop mathematical skills would also be worthwhile.

Summary

At the College of William and Mary, we have used the matrix approach to integrate the teaching and development of quantitative skills across the curriculum. After identifying critical quantitative skills and applications, faculty members in the department systematically incorporate quantitative activities in geoscience courses throughout the curriculum, for both majors and non-majors. For this approach to be successful, faculty members must be willing to discuss their courses in detail and change course content and activities as necessary. Students receive a consistent message from all faculty members that quantitative skills are important in the earth sciences. The particular skills and applications that we have listed in the matrix may or may not be applicable to other departments. Individual departments would need to tailor the matrix approach to the skills and applications they identify as most important for their students. However, we think that the *process* of using the matrix approach, as described in this paper, will be useful to others interested in developing quantitative skills across the curriculum.

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