JOURNAL OF GEOSCIENCE EDUCATION **62**, 668–678 (2014)

Design and Assessment of a Skills-Based Geoscience Curriculum

Carl E. Renshaw[1,a]

ABSTRACT

There is increasing interest in science curricula that engage students in scientific practices to deepen their understanding of the core ideas of the field. There are, however, few examples of their designs or assessments available for use as guides for understanding the strengths and weaknesses of particular designs. We offer a summary of our experience in designing and assessing a skills-based geoscience curriculum contextualized within a recently proposed, generalized framework for curricular designs and assessment. Our novel approach to curriculum assessment, with its emphasis on ensuring that the skills highlighted in different courses align with the objectives of the curriculum, is meant to complement more-direct assessments of student mastery of various skills. Assessment results reveal good alignment of course and curricular objectives, in some cases, whereas other parts of the curriculum require refinement. The most challenging of which is the failure of the introductory-level courses to emphasize the process of science. That result is consistent with recent work demonstrating that current approaches to teaching the nature of science are often ineffective. Thus, some of the most challenging problems with more traditional curricula, such as how to help students develop a more-advanced understanding of the nature of science, are not necessarily solved by focusing curricula on the integration of skills with content. *© 2014 National Association of Geoscience Teachers*. [DOI: 10.5408/13-100.1]

Key words: curriculum, assessment

INTRODUCTION

The geoscience education literature is replete with examples of the design and assessment of individual courses and even offers some examples of integrating specific skills (e.g., quantitative analyses, writing, or field-based instruction) across multiple courses (e.g., Macdonald and Bailey, 2000; Knapp et al., 2006; Leydens and Santi, 2006). Far less common, at least at the undergraduate level, are examples of curriculum design as used in this article, i.e., the design and sequencing of a series of undergraduate courses from introductory to advanced levels (Kelso and Brown, 2009). Almost nonexistent, in the geoscience literature, are quantitative assessments of undergraduate curricula.

Beyond geosciences, considerable discussion of curriculum design has been exchanged; yet, at least at the postsecondary level, there has been limited quantitative curriculum assessment. Most existing quantitative assessments are focused on training in professional skills, particularly in the medical fields (e.g., Roxburgh et al., 2008; Hall, 2014). Doll (1993) argues that most of those evaluations are "modernistic" because they seek to determine the extent to which a curriculum achieves well-defined educational goals, with learning a specifically intended, directed, and controlled outcome—one that can be measured. That approach to curriculum design and assessment has been criticized for reducing the complexity of the curriculum to easily measurable objectives that primarily address lower-order behaviors, rather than higher-order thinking. As an alternative, Doll (1993) argues that postmodern curricular development should follow Dewey (1938) and emphasize the exploration of the unknown, allowing educational ends to arise from within the process of experiential activity, with learning being a byproduct of that activity (Koo Hok-chun, 2002). This approach to curricular design is consistent with the Hargreaves (1994) argument that the skills required to succeed in the postmodern world include inquiry, information gathering, analysis, and other aspects of learning how to learn in an engaged and critical way. The Doll (1993) postmodern approach to curricular development has been criticized for being overly vague, difficult to assess, and, to a certain extent, unrealistic, idealistic, and impracticable (Koo Hok-chun, 2002).

The Next Generation Science Standards (NGSS) might be seen as an attempt to reconcile modern and postmodern approaches to curriculum development by explicitly linking core disciplinary ideas and crosscutting concepts with scientific practices, where the term *practice* is used rather than *skill* to stress that engaging in scientific inquiry requires the use of both knowledge and skill simultaneously (NAS, 2012). The NGSS is a flexible model for curricular design, in which the focus is not on particular courses and their content (as typical of a purely modernistic model) but, rather, is on the integration of knowledge and skills across the curriculum, with content learning being a consequence of directed experience in scientific practices (as emphasized in the postmodern model). In the NGSS model, the curriculum becomes more than just a course-by-course description of core content to be learned and, instead, complements required core content with a description of the skills or practices expected of all students by the completion of their degrees. Although grounded in foundational ideas, the emphasis of the NGSS on scientific practices allows for an exploration of the unknown, with the specific educational outcomes arising from activities that allow the student to practice the skills required for students to quickly adapt to fields, both within geosciences and beyond, where new ideas and techniques rapidly emerge and where tenure at any one

---

Received 11 June 2014; revised 25 October 2013; accepted 21 July 2014; published online 19 November 2014.

[1] Department of Earth Sciences, Dartmouth College, Hanover, New Hampshire 03755, USA

[a] Author to whom correspondence should be addressed. Electronic mail: Carl.Renshaw@Dartmouth.edu. Tel.: 603-646-3365. Fax: 603-646-3922.

position is often limited (Manduca et al., 2008). Although the generality of a skills-based curriculum makes it easier to adapt to a variety of student needs, it also presents a secondary challenge beyond its design; namely, how is it assessed? The question of assessment is particularly important given the increasing demands of governmental and accrediting agencies for greater academic accountability (Middaugh, 2007).

The idea of skills-based geoscience curricula at the college level is not necessarily novel, but there are few examples in the literature of their design or their assessments for use as guides to understanding the strengths and weaknesses of particular programs. In that spirit, I offer a brief summary of our experience in designing and assessing a skills-based geoscience curriculum contextualized within the framework of a recently proposed model for curriculum design and assessment (Hall, 2014). Although I briefly describe the development of our curriculum, the emphasis here is on the novel approach to assessment. That assessment is an ongoing process, and thus, I present here a status update rather than a complete case study. Our assessment efforts, however, have already provided important feedback regarding how our curriculum can be improved, which aligns with recent work suggesting that current approaches to teaching the nature of science may not be effective (Abd-El-Khalick, 2006; Nadelson and Viskupic, 2010).

CURRICULUM DESIGN

Motivation

By many metrics, Dartmouth already had a strong undergraduate geoscience curriculum before our curricular redesign. During the course of this study, we had a faculty of 10, averaged 10–15 majors per year split between two majors, and supported about 20 graduate students. Almost all classes were taught by regular faculty, with teaching assistants taking on only limited teaching roles in introductory laboratory sections. We offered (and continue to offer) almost all core geoscience courses most frequently provided by geology departments in the U.S. (Drummond and Markin, 2008). In addition, Dartmouth is among the top 25 U.S. institutions in producing undergraduates that go on to earn doctorates in geosciences, both in absolute numbers of undergraduate majors going on to earn doctorate degrees and in "institutional–yield ratio" (Fiegener and Proudfoot, 2013), i.e., the number of doctorates earned normalized by the total undergraduate enrollment (see Appendix A).

By the early 2000s, our traditional, prescribed–course-based (i.e., "modernistic") curriculum was becoming increasingly unwieldy as the number of sub-disciplines and skills needed by our graduates increased and evolved (Heath, 2003) and the careers pursued by our graduates diversified. The distribution of careers among our alumni is generally similar to national averages (AGI, 2001) but with a greater fraction of our alumni pursuing nongeoscience careers when compared with the national average (about 30% versus about 10% nationally).

Because the number of courses required in a major is more or less fixed, increasing the number of required core courses as the discipline expands leads to a reduction in the number of elective courses a student can take, reducing the flexibility that allowed students to adapt their course selections to their career interests. Also, focusing on individual core courses does not, by itself, shed light on how the different courses interact pedagogically. This latter point is important because of increasing demands from institutional and accrediting agencies for clear statements of anticipated student learning outcomes not only at the course level but also at the department level, where learning outcomes are expected to be aligned with each other.

Framework for Curricular Design

Recently, Hall (2014) proposed a framework for curricular design and assessment based on the earlier work of Glatthorn (1987) and Print (1993). That framework envisioned the process of curriculum design and assessment to involve four key steps: the first two focused on design the latter two on assessment. In Step 1—*benchmarking*—key curricular objectives identified by professional bodies and peer institutions are reviewed. In Step 2—*evidencing*—a correspondence is established between the benchmark standards and the proposed curricular elements. In the first of the two assessment steps, *knowing*—the congruence between the planned and delivered curriculum—is assessed. In the Step 4—*applying*—the extent to which students are achieving the curricular objectives is assessed. Those steps generally align with the four foundational questions for curriculum design originally proposed by Tyler (1949):

1. What educational purposes should the curriculum seek to achieve?
2. What learning experiences are useful in attaining these objectives?
3. How should these learning experiences be organized?
4. How can the learning experiences be evaluated?

Although we were unaware of that framework for curricular design when we revised our curriculum, a post hoc review of our process reveals that it generally followed the framework.

As envisioned in the framework, we began our curriculum design with a process of benchmarking against peer institutions and professional bodies. Specifically, to define the sets of key concepts and skills that would define our curriculum, we used a "backward design" (Wiggins and McTighe, 2005) approach in which we started by outlining what a graduate of our program should know and be able to do. For guidance, we grouped common concepts and skills that appeared repeatedly in geoscience program-assessment instruments used at peer institutions (available at the Science Education Resource Center, http://www.serc.edu). Ultimately, we identified five categories of key concepts and skills and assigned each of our courses into one of those categories (Table I). We then defined the curriculum so that all majors had to take at least one course in each course category, thus ensuring that each student took at least one course placing particular emphasis on each set of concepts and skills. This approach to curriculum design might be viewed as a hybrid between modern and postmodern approaches. Consistent with the dictates of postmodern design, the curriculum does not define specific content to be learned. Instead, the specific content learned is a byproduct of students practicing specific skills and concepts in the courses they elect. However, consistent with modern curricular design, our skills-based curriculum has well-

TABLE I: Student learning goals and laboratories for the *Cyrosphere* and *Earth Systems Science Earth Laboratories* modules.

Key Concepts and Skills	Example Courses
Introductory Courses (*one course required*)	
Concepts of geologic time and geologic scales	How the Earth Works
Earth's origins	Environmental Change
The use of maps and spatial data	Evolution of Life and Earth
The process of science and the evolution of scientific concepts	
Earth as a dynamic system including physical, chemical, and biological interactions	
The impact of geology and natural resources on the evolution of life and vice versa	
The concept of uncertainty as it applies to our understanding and analysis of Earth processes, resources, and hazards.	
Collection and Analysis of Earth Science Data (*one course required*)	
Collection and interpretation of earth science data	Earth's Climate: Past, Present, Future
Collection of field observations	Meteorology
Quantifying uncertainty	Environmental Geology
Core Methods and Concepts (*4–6 courses required*)	
Origin of earth materials	Mineralogy
Mineral transformations	Structural Geology
Structure and mechanics of earth materials	Sedimentary Systems
Co-evolution of Earth and life	
Geotectonics	
Core field methods	
Working in groups	
Quantitative Analysis of Earth Systems (*one course required*)	
Simplification/modeling of complex systems for quantitative analysis	Geophysics
Quantitative analysis of earth systems	Hydrogeology
Limits of data/knowledge	Geochemistry
Advanced Topics (*one course required*)	
In depth exploration of a specialized topic at an advanced level	Environmental Isotope Geochemistry
Reading the scientific literature	Advanced Quaternary Paleoclimatology
Abstract writing	Geobiology

defined educational goals (i.e., the mastery of specific skills) that are, in principal, measureable.

Although developed independently, our key concepts and skills categories are consistent with the U.S. National Research Council's Framework for K-12 Science Education (FSE), which is the basis for the NGSS. As with our approach, the FSE does not seek to define course structure but, rather, to define a vision for science education. In that vision, students, during multiple years of school, engage in scientific practices that deepen their understanding of the core ideas in a field (Quinn et al., 2012). Consistent with the postmodern approach, in emphasizing practices over content, the FSE seeks to help students understand that theory development, reasoning, and testing are components of a larger ensemble of activities defining the nature of science, which includes teamwork, specialized ways of communicating, the development of models to represent systems or phenomena, the making of predictive inferences, and the testing of hypotheses by experiment or observation (Quinn et al., 2012). To achieve that vision of science education, the FSE identifies eight core practices intended to develop students' understanding of the nature of science and engineering. Those core practices include "planning and carrying out investigations" and "analyzing and interpreting data," both of which are consistent with the skills that define our Collection and Analysis of Earth Science Data course category (Table I). Similarly, the FSE core practices of "developing and using models" and "using mathematics and computational thinking" align with the skills that define our Quantitative Analysis of Earth Systems course category. Finally, the FSE core practices of "asking questions and defining problems" as well as "engaging in argument from evidence" are central to the "process of science and the evolution of scientific concepts" element of our introductory level course category. Demonstrating the congruence between our curricular design and the FSE represents the second step in the curricular design framework—evidencing.

ASSESSMENT DESIGN

Within the framework for curricular design and assessment described above, opportunities for assessment are

TABLE II: Explanation and scoring system for the conceptual understanding rubric.

Questions	Course Category Most Emphasizing Skill[1]
Question 1	
This course improved my quantitative and analytical skills	Quantitative Analysis of Earth Systems ($p = 0.020$)
Question 2	
This course improved my ability to communicate scientific concepts, data, and results in written and oral form	Advanced Topics ($p = 0.099$)
Question 3	
This course improved my familiarity with sources and the use of scientific literature	None (see text)
Question 4	
This course improved my familiarity with the process of science	Collection and Analysis of Earth Science Data ($p = 0.089$)
Question 5	
This course improved my ability to obtain, analyze, and interpret scientific data	Collection and Analysis of Earth Science Data ($p = 0.027$)

[1] Misconceptions may or may not be present in levels 0–3.

contained within the final two steps, *knowing*—determining the congruence between the planned and delivered curriculum—and *applying*—determining whether students are achieving the curricular objectives. Determining whether students are achieving curricular objectives is sometimes done using postcourse surveys or capstone exams. Such an approach, however, can be inefficient and redundant. If a course emphasizes a particular skill, and if the student's summative evaluation (e.g., final exam or project) in that course reflects their mastery of the emphasized skill, then the summative evaluation from that course presents a richer assessment of a student's mastery of that skill than can be determined using a postcourse survey. Thus, we approached the assessment of our curriculum by focusing on the first of the two assessment steps, the congruence between the planned and delivered curriculum. In our case, our hypothesis was that courses within a particular category emphasized the skills that define that category.

Rather than relying on course syllabi to determine what skills a particular course emphasized, we instead opted to directly ask the students at the completion of each course which skills they thought the course emphasized. We recognized the potential for a student to misinterpret the purpose of a course. However, because clarity of goals is an essential element of effective teaching, such a misunderstanding, in most cases, likely indicates a failure of the course to serve its curricular purpose. Misinterpreting the goals of a course also likely represents a failure of the summative evaluation of the course to reflect a student's mastery of the targeted skills. We also recognized that the perception of emphasis on a skill does not imply mastery of that skill, a situation that should be reflected in the student's summative evaluation, but, again, our objective in this assessment was to investigate the alignment of course and curricular objectives.

To determine which skills students thought a particular course emphasized, we added five questions to the online course evaluation survey that students are asked to complete at the end of each course (Table II). The five questions asked the student to what extent they agreed that the course improved their familiarity or ability in that skill. Students ranked each skill on a five-point scale, ranging from strongly agreeing that the course improved their familiarity or ability in that skill (ranking = 1) to strongly disagreeing that the course improved their familiarity or ability in that skill (ranking = 5). Students could also select *not applicable*. We cautioned the student that courses were designed to focus on particular skills, so not all skills listed may have been addressed. Some caution was also warranted in interpreting the results from that survey because no attempt was made to formally validate the skill-ranking questions.

In the analysis of our data, I also used one item from the standard course evaluation. That question asked the student to rate the overall quality of the course on a five-point scale, ranging from excellent (rating =1) to poor (rating = 5). Separate analyses of the student responses to other questions on the course evaluation that addressed specific aspects of course quality, such as the extent to which course objectives were clear, assessment of how much was learned in the course, and course organization, were found to be highly correlated with assessment of the overall course quality. Thus, only the overall assessment of course quality was used here.

Between fall 2009 and spring 2013, end-of-class online evaluations containing the five skill-ranking questions were given in 86 different classes. Except for the introductory course category, the distribution of courses offered between the different course categories was similar, with 10–20 courses in each category. There were 29 courses offered in the introductory course category.

Students completed the online course evaluations outside of class anytime within a window that extended from the last week of the term to the fourth day of the next term. Students were not required to complete the evaluations; however, those that did complete the evaluation could see their course grades earlier than those that did not complete the evaluations.

The online course evaluations had four or five sections, each with five to 10 questions. The first section asked about student background, the second section about course design and effectiveness, the third section about faculty effectiveness, the fourth section about laboratory sections (if applicable), and the fifth section contained the five skill-ranking questions.

TABLE III. Summary of skill rankings for each course category.

Course Category[1]\Skill	Quantitative[2]	Communicate	Literature	Nature of Science	Data Analysis
Introductory (29/1,981)	2.33 (0.38)	2.20 (0.31)	2.38 (0.35)	2.13 (0.31)	2.20 (0.39)
Data analysis (16/182)	1.83 (0.35)	1.60 (0.38)	2.08 (0.67)	1.58 (0.35)	1.44 (0.33)
Core methods (18/217)	2.12 (0.80)	1.92 (0.31)	2.19 (0.41)	2.07 (0.80)	1.84 (0.28)
Quantitative (12/136)	1.66 (0.25)	1.74 (0.30)	1.96 (0.45)	1.79 (0.23)	1.83 (0.57)
Advanced (11/145)	1.58 (0.41)	1.65 (0.57)	1.66 (0.39)	1.56 (0.39)	1.54 (0.55)

[1] Values in parentheses indicate (number of courses/total number of students).
[2] Mean (SD), lower mean values indicate greater emphasis.

RESULTS

Responses

The 86 different classes given the skill-ranking questions had a total enrollment of 2,661 students. The number of courses and total number of students in each course category are summarized in Table III. Survey completion rates averaged 88% and ranged from a low of 77% in the advanced topics courses to a high of 90% in the introductory courses.

Average student rankings ranged from 1.44 to 2.38 and are summarized in Table III. Lower-ranking values indicate the student more-strongly agreed the course improved their familiarity or ability with that skill. The average ranking for each skill across all courses were similar, except for the skill of using the scientific literature (single-factor ANOVA, $p = 0.002$). Familiarity with sources and the use of scientific literature was, on average, slightly less emphasized in all courses relative to the other skills.

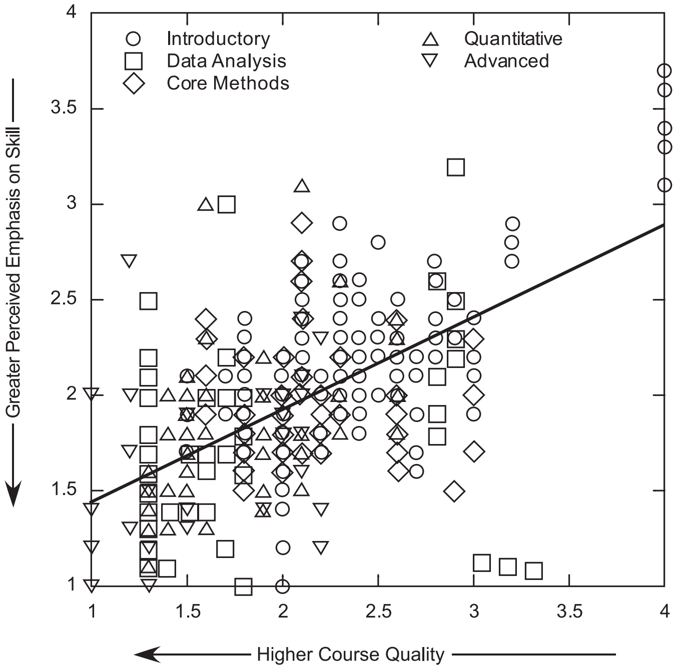

FIGURE 1: Average perceived emphasis on skill ranking for courses offered in the years 2009–2013 as a function of reported course quality. Each point indicates the average values for an individual course. Symbols indicate rankings for different categories of courses. Solid line is the best linear fit for the entire data set ($r^2 = 0.34$).

Course Quality Effect

Across all courses, the rankings of the skills were correlated ($r^2 = 0.34$) with overall course quality (Fig. 1). Higher-quality courses were generally ranked higher across all skills than lower-quality courses. To remove the effect of course quality on the relative rankings, only the residuals of the rankings were analyzed when comparing different categories of courses. To do that, for each skill, a best linear fit of course quality versus rankings was determined, and the residuals were determined as the difference between each ranking and the best linear fit. To determine whether a particular category of courses placed significantly more or less emphasis on a particular skill, single-factor ANOVAs were performed to compare the residuals among the different categories of courses. None of the ANOVAs were significant when all the categories of courses were considered. Closer inspection of the mean and variance of the residuals for each course category revealed that, although the mean residual of the different skills rankings for courses in the Core Concepts and Methods category was typically close to zero (indicating that those types of courses, on average, tended not to emphasize a particular skill more or less than other types of courses), the variance of the residuals for Core Concepts and Methods courses was, in some cases, more than a factor of three larger than the corresponding variances of the residuals for other course categories. Thus, the particular skill emphasized by Core Concepts and Methods courses varied more from course to course within that category in comparison to other course categories.

Removing the Core Concepts and Methods courses from the analysis, the single-factor ANOVAs for four of the five skills were significant ($p < 0.05$), indicating that each of those four types of skills was significantly more or less emphasized in at least one category of courses (Table II). The exception was that no category of courses placed particularly more or less emphasis on the use of scientific literature ($p = 0.26$). Taken together with the above result indicating that across all courses the use of scientific literature was slightly less emphasized relative to the other skills, these results indicate a failure of the courses in our curriculum to appropriately address that skill.

Contrast Analyses

For the four skills with statistically significant ANOVAs, follow-up contrast analyses were done to compare, for each skill, the residuals of the rankings within each course category. Specifically, for each skill type, we used a single-factor ANOVA to compare either the highest or lowest average residual across the different course categories to the

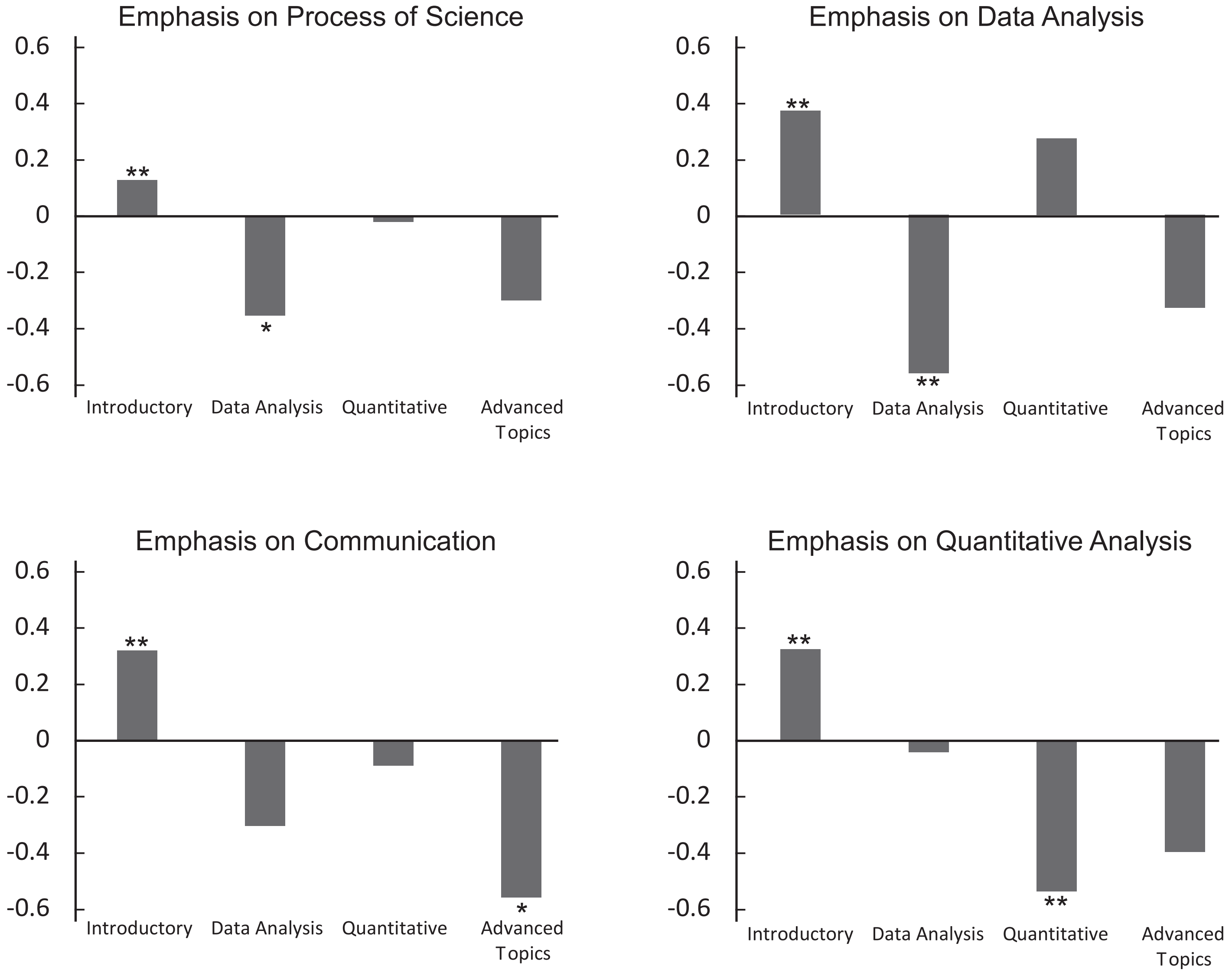

FIGURE 2: Residual skill rankings for the different course types after the effect of course quality was removed. Lower rankings indicate students more-strongly agreed that course type improved their familiarity or ability with the given skill. ANOVAs on the residuals for each skill type shown are significant ($p < 0.05$). Follow-up contrast analyses (single-factor ANOVAs) compared either the highest or lowest average residual across the different course categories to the combined residuals of the other course categories for that skill. Course types with average residuals significantly different ($p < 0.05$) than the other course types are indicated by two asterisks (**). Marginally significant differences ($p < 0.1$) are indicated with a single asterisk (*).

combined residuals of the other course categories for that skill (Fig. 2).

Consistent with the design of the curriculum, students report that the Collection and Analysis of Earth Science Data courses placed significantly greater ($p = 0.027$) emphasis on obtaining, analyzing, and interpreting scientific data. In contrast, our introductory level courses placed significantly less ($p = 0.011$) emphasis on the analysis of scientific data. Also consistent with the design of the curriculum, students reported that Quantitative Analysis of Earth Systems courses placed significantly greater ($p = 0.02$) emphasis on quantitative and analytical skills. Here, too, introductory level courses were reported to place significantly less ($p < 0.001$) emphasis on quantitative and analytical skills. The final two significant contrast effects revealed that, relative to our other types of courses, students report that our introductory level courses placed significantly less emphasis on the communication of scientific concepts, data, and results in written and oral form ($p = 0.006$) and on the process of science ($p = 0.007$). The Advanced Topics course was marginally significant for placing more emphasis on communication of scientific concepts, data, and results ($p = 0.099$), and Collection and Analysis of Earth Science Data courses was marginally significant in placing more emphasis on the process of science ($p = 0.089$).

DISCUSSION

The assessment results indicated that although some aspects of our curriculum were working as intended, other parts required refinement. Among the successes was the alignment of the skills emphasized in the Collection and Analysis of Earth Science Data and Quantitative Analysis of Earth Systems categories with the skills that defined those categories. That the skills those courses emphasized were not particularly emphasized in our introductory level courses can also be viewed as a success of the curriculum. That is not to say that data analysis and quantitative skills should not be addressed in introductory level courses, but rather that, according to our curriculum design, our introductory level courses should place more emphasis on understanding the process of science and the evolution of scientific concepts and, relatively, less emphasis on data or quantitative analyses.

That the skills emphasized in Core Methods and Concepts courses varied from course to course was also consistent with the design of the curriculum. That is, those courses were not designed to place particular emphasis on any one of the skills included in our assessment. For technical reasons, we were limited to adding only five questions to the online course evaluation. If we could have added a sixth question, we would have asked the students to rank the relative emphasis placed on working in groups, a key skill defining the Core Methods and Concepts category.

Among the areas of the curriculum that, according to the assessment results, needed correction was the failure of the Advanced Topics courses, or any other category of course, for that matter, to emphasize the use of scientific literature. It is difficult to argue that our students are mastering that critical skill if they report that, on average, none of their courses placed particular emphasis on in its importance. That deficiency could be addressed by reminding our faculty to include greater attention to the scientific literature in our Advanced Topics courses.

Somewhat more challenging to address is the failure of Collection and Analysis of Earth Science Data courses to emphasize the communication of scientific concepts, data, and results in written and oral form despite scientific discourse being a key skill defining that course category. The idea that scientific discourse, rather than being emphasized only in one particular category of courses, is instead emphasized in all categories of courses is rebutted by the fact that the average ranking for this skill is no different than the average rankings of the other skills (except, as noted earlier, scientific literature). Interestingly, the assessment reveals that Advanced Topics courses were marginally significant for placing more emphasis on scientific communication. That may reflect partially successful attempts in those courses to follow the dictates of the curriculum and emphasize familiarity with sources and the use of scientific literature. This focus was, at best, only partially successful because students did not rank Advanced Topics courses as particularly affecting their familiarity and use of the scientific literature (Table II). However, to the extent that the primary scientific literature is discussed in those courses, students may rank those courses as placing somewhat more emphasis on science communication. To address the lack of emphasis on scientific communication in the curriculum, we could decide either to place greater emphasis on scientific communication in our Collection and Analysis of Earth Science Data courses or, alternatively, to move that skill to the Advanced Topics courses and give it greater attention in those courses. That Advanced Topics courses already gave some emphasis to scientific communication suggests that moving the skill to the Advanced Topics category might be appropriate.

Perhaps the biggest challenge indicated by the assessment results was the failure of the introductory courses to emphasize, at least as perceived by the students, the process of science. We recognize that students can sometimes be unaware of the positive effect an exercise or course has on their mastery of a particular skill (Renshaw and Taylor, 2000), and thus, students in our introductory courses may not have recognized the effect those courses had on their understanding of the process of science. However, that assessment result is consistent with recent work demonstrating that current approaches to teaching the nature of science are often ineffective, resulting in students retaining naïve conceptions on the nature of science, even as college graduates (Abd-El-Khalick 2000; Moss et al., 2001; Abd-El-Khalick 2006; Nadelson and Viskupic 2010). A potentially important distinction in terminology is worth noting. In designing and assessing our curriculum, we were consistent and always described the skill as "familiarity with the process of science." In the science-education literature, the idea we imagined in creating the curriculum is referred to as the "nature of science." Schwartz et al. (2012) argue that the two terms are not strictly synonymous. That is, in speaking of the *process of science* as a skill, they argue, we are really referring to what they term the "nature of scientific inquiry," rather than the broader suite of elements that make up the nature of science, which includes, for example, its tentative, creative, and subjective aspects. The distinction between terminologies is important for understanding the strengths and weaknesses of different approaches to teaching the nature of science (Khishfe and Abd-El-Khalick, 2002; McDonald, 2010), but the subtlety between the phrases *process of science* and *nature of science* is likely not perceived by the students completing the skill-ranking survey.

In many cases, students failed to develop an understanding of the process of science in introductory courses partly because those courses often emphasize science content knowledge more than they do the nature of science (Abd-El-Khalick, 2000; Bickmore et al., 2009). However, emphasizing content over process may not result in effective learning because a fundamental understanding of the nature of science is critical to learning science (Alters, 1997; NRC, 1998; Nadelson and Viskupic, 2010).

There is some suggestion that students can gain an understanding of the process of science through implicit exposure to the construct when engaging in scientific activities (Ryder, et al., 1999). This may explain students' perceptions of the marginally significant more emphasis placed on the process of science in Collection and Analysis of Earth Science Data courses. By engaging in the analysis of data, students may be gaining an implicit understanding of the process of science. If the understanding of the process of science is linked to engaging in scientific practices, it may be unrealistic to set the understanding of the process of science as a goal for introductory courses. Instead, students develop an understanding of the process of science as they proceed through a curriculum that emphasizes the different elements of scientific practice. Some support for this idea comes from our recent survey of alumni, in which almost three-quarters of the nearly 300 respondents reported that Dartmouth provided effective training in understanding the process of science.

However, other studies have shown that the assumption that engaging in scientific practices will develop one's understanding of the nature of science is flawed (Khishfe and Abd-El-Khalick, 2002; Schwartz and Lederman 2008). For example, Nadelson and Viskupic (2010) found a poor correlation between the number of courses taken by undergraduate geoscience students and their understanding of the nature of science. Instead, research during the past 2 decades has found that the nature of science is best taught using an explicit and reflective approach (Abd-El-Khalick et al., 1998; Abd-El-Khalick and Akerson, 2004; McDonald, 2010).

An alternative explanation for why students indicated a marginally significant emphasis on the process of science in Collection and Analysis of Earth Science Data courses is that the nature of those courses may only be reinforcing students' naïve "logical positivist" conceptions on the nature of science (Bickmore et al., 2009). That is, in analyzing data, students may be reinforcing their perception that the process of science is solely focused on the use of data to verify hypotheses, rather than the more-modern view that data are meant to falsify hypothesis. Further, students' limited focus on the data analysis component of the process of science may indicate that they fail understand that abstract reasoning, tentative conclusions, and creativity are all equally important aspects of the nature of science (Bickmore et al., 2009).

CONCLUSIONS

The vitality of the geosciences is partly attributable to their dynamic, integrative, and expansive nature (Gabler and Frank, 2005). Those traits result in an evolving science, and, as the science evolves, so too must the curriculum. With most geoscience undergraduates not planning to pursue careers in the traditional mining and energy industries (Wilson, 2012), the traditional curriculum must evolve to accommodate those students interested in nontraditional careers. Some guidance in how geoscience curricula should evolve is provided by the NGSS and its focus on the integration of knowledge and skills over course-by-course descriptions of core content to be learned. Currently, however, there are few examples of the implementation or assessment of a skills-based curriculum at the undergraduate level.

The novel approach to curriculum assessment presented here, with its emphasis on ensuring that the skills different courses emphasized align with the objectives of the curriculum, is meant to complement more-direct assessments of student mastery of different skills. Determining whether the designs of different courses align with the dictates of the overall curriculum is an important first check of curriculum integrity.

The assessment results indicated that some aspects of our curriculum were working as intended. Students reported that the skills emphasized in the Collection and Analysis of Earth Science Data and Quantitative Analysis of Earth Systems course categories aligned well with the skills that defined those categories.

The assessment results also indicated that some the areas of the curriculum needed to be refined. The most challenging of which was the failure of the introductory courses to emphasize, at least as perceived by the students, the process of science. That result is consistent with recent work demonstrating that current approaches to teaching the process of science are often ineffective (Abd-El-Khalick, 2000; Moss, et al., 2001; Abd-El-Khalick 2006; Nadelson and Viskupic, 2010), often because introductory courses emphasize content rather than the process of science (Abd-El-Khalick, 2000; Bickmore et al., 2009).

The shift to a skills-based curriculum offers new opportunities to adapt course offerings to the increasing variety of student needs. However, as our results demonstrate, doing so is not a panacea. Some of the most-challenging problems with more traditional curricula, such as how to help students develop a more advanced understanding of the nature of science, are not necessarily solved by focusing curricula on the integration of skills with content. But by highlighting the development of different skills across the entire curriculum, skills-based curricula make it easier to identify how different courses work (or do not work) together to create an integrated whole that ensures that students become skilled learners that can quickly adapt to rapidly evolving and expanding disciplines, both within geosciences and beyond.

REFERENCES

Abd-El-Khalick, F. 2000. Improving science teachers' conceptions of nature of science: A critical review of the literature. *International Journal of Science Education*, 22:665–701.

Abd-El-Khalick, F. 2006. Over and over again: College students' views of the nature of science. *In* Flick, L.B., and Lederman, N.G. eds., Scientific inquiry and nature of science: implications for teaching, learning, and teacher education. Dordrecht, Netherlands: Klumer Academic Publishers, p. 389–425.

Abd-El-Khalick, F., and Akerson, V.I. 2004. Learning about nature of science as conceptual change: Factors that mediate the development of preservice elementary teachers' views of nature of science. *Science Education*, 88(5):785–810.

Abd-El-Khalick, F., Bell, R.L., and Lederman, N.G. 1998. The nature of science and instructional practice: Making the unnatural natural. *Science Education*, 82(4):417–437.

(AGI) American Geological Institute. 2001. Report on the status of academic geoscience departments. Washington, DC: AGI.

Alters, B.J. 1997. Whose nature of science? *Journal of Research in Science Teaching*, 34(1):39–55.

Bickmore, B.R., Thompson, K.R., Grandy, D.A., and Tomlin, T. 2009. On teaching the nature of science and the science-religion interface. *Journal of Geoscience Education*, 58(3):168–177.

Dewey, J. 1938. Logic: A theory of inquiry. New York: Holt & Co.

Doll, W.E. 1993. A post-modern perspective on curriculum. New York: Teachers College Press.

Drummond, C.N., and Markin, J.M. 2008. An analysis of the bachelor of science degree in geology as offered in the United States. *Journal of Geoscience Education*, 56(2):113–119.

Fiegener, M.K., and Proudfoot, S.L. 2013. Baccalaureate origins of U.S.-trained S&E doctorate recipients. Arlington, VA: National Science Foundation, National Center for Science and Engineering Statistics.

Gabler, J., and Frank, D.J. 2005. The natural sciences in the unversity: Change and variation in the 20th century. *Sociology of Education*, 78(3):183–206.

Glatthorn, A.A. 1987. Curriculum leadership. Glenview, IL: Scott, Foresman and Company.

Hall, C.E.A. 2014. Toward a model of curriculum analysis and evaluation—Beka: A case study from Australia. *Nurse Education Today*, 34:343–348.

Hargreaves, A. 1994. Changing teachers, changing times. London, UK: Cassell.

Heath, C.P.M. 2003. Geological, geophysical, and other technical and soft skills needed by geoscientists employed in the North American petroleum industry. *AAPG Bulletin*, 87(9):1395–1410.

Kelso, P.R., and Brown, L.M. 2009. Integration of field experiences in a project-based geoscience curriculum. *In* Whitmeyer, S.J., Mogk, D.W., and Pyle, E.J., eds., Field geology education: Historical perspectives and modern approaches. Boulder, CO: Geological Society of America Special Paper 461.

Khishfe, R., and Abd-El-Khalick, F. 2002. The influence of explicit reflective versus implicit inquiry-oriented instruction on sixth grader's views of nature of science. *Journal of Research in Science Teaching*, 39(7):551–578.

Knapp, E.P., Greer, L., Connors, C.D., and Harbor, D.J. 2006. Field-based instruction as part of a balanced geoscience curriculum at Washington and Lee University. *Journal of Geoscience Education*, 54(2):103–108.

D. Koo Hok-chun, 2002. Quality education through a post-modern curriculum. *Hong Kong Teacher's Centre Journal*, 1:56–73.

Leydens, J.A., and Santi, P. 2006. Optimizing faculty use of writing as a learning tool in geoscience education. *Journal of Geoscience Education*, 54(4):491–502.

Macdonald, R.H., and Bailey, C.M. 2000. Integrating the teaching of quantitative skills across the geology curriculum in a department. *Journal of Geoscience Education*, 48:482–486.

Manduca, C.A., Macdonald, H. and Feiss, G. 2008. Education: Preparing students for geosciences of the future. *Geotimes*, 53(4):59.

McDonald, C.V. 2010. The influence of explicit nature of science and argumentation instruction on preservice primary teachers' views of nature of science. *Journal of Research in Science Teaching*, 47(9):1137–1164.

Middaugh, M.F. 2007. Creating a culture of evidence: Academic accountability at the institutional level. *New Directions for Higher Education*, 140:15–28.

Moss, D.M., Abrams, E.D., and Robb, J. 2001. Examining student conceptions of the nature of science. *International Journal of Science Education*, 23:771–790.

Nadelson, L.S., and Viskupic, K. 2010. Perceptions of the nature of science by geoscience students experiencing two different courses of study. *Journal of Geoscience Education*, 58(5):275–285.

Print, M. 1993. Curriculum development and design. St. Leonards, Australia: Allen and Unwin.

Quinn, H., Schweingruber, H. and Keller, T. 2012. A framework for K-12 science education: Practices, crosscutting concepts, and core ideas. Washington, DC: National Academies Press.

Renshaw, C.E., and Taylor, H.A. 2000. The educational effectiveness of computer-based instruction. *Computers and Geosciences*, 26:677–682.

Roxburgh, M., Watson, R., Holland, K., Johnson, M., Lauder, W., and Topping, K. 2008. A review of curriculum evaluation in United Kingdom nursing education. *Nurse Education Today*, 28:881–889.

Ryder, J., Leach, J., and Driver, R. 1999. Undergraduate science students' images of science. *Journal of Research in Science Teaching*, 36(2):201–220.

Schwartz, R.S., and Lederman, N.G. 2008. What scientists say: Scientists' views of nature of science and relation to science context. *International Journal of Science Education*, 30(6):727–771.

Schwartz, R.S., Lederman, N.G., and Abd-El-Khalick, F. 2012. A series of misrepresentations: A response to Allchin's whole approach to assessing the nature of science understandings. *Science Education*, 96(4):685–692.

Tyler, R.W. 1949. Basic principles of curriculum and instruction. Chicago, IL: University of Chicago Press.

Wiggins, G., and McTighe, J. 2005. Understanding by design. New York: Pearson.

Wilson, C. 2012. Status of recent geoscience graduates. Alexandria, VA: American Geosciences Institute.

APPENDIX A

The baccalaureate origins of students earning doctorates in geosciences were determined as reported by the National Science Foundation Survey of Earned Doctorates program (http://webcaspar.nsf.gov/). For each institution included in the report, the total number of undergraduates going on to earn geoscience PhD degrees during the years 1966–2011 was summed and expressed as the average number of earned doctorates per year (Table AI). To determine the institutional yield ratio, the average number of earned doctorates per year was divided by the institution's total undergraduate enrollment in 2010, as reported by the Integrated Postsecondary Education Data System of the National Center for Education Statistics (http://nces.ed.gov/ipeds/deltacostproject/) (Table AII).

TABLE AI. Total number of undergraduates going on to earn geoscience PhD degrees during the years 1966–2011.

Rank	Institution	Doctorates/Year
1	University of California (Berkeley)	6.67
2	University of Wisconsin (Madison)	4.42
3	Stanford University (Stanford, CA)	4.18
4	Carleton College (Northfield, MN)	4.11
5	Pennsylvania State University (State College)	4.00
6	Massachusetts Institute of Technology (Cambridge)	3.71
7	University of California (Los Angeles)	3.64
8	University of Washington (Seattle)	3.64
9	Dartmouth College (Hanover, NH)	3.58
10	Brown University (Providence, RI)	3.47
11	University of California (Santa Barbara)	3.33
12	University of Illinois (Urbana–Champaign)	3.31
13	Cornell University (Ithaca, NY)	3.29
14	University of Texas (Austin)	3.29
15	Harvard University (Cambridge, MA)	3.24
16	University of Colorado (Boulder)	3.24
17	California Institute of Technology (Pasadena)	3.22
18	University of Michigan (Ann Arbor)	3.13
19	Colorado School of Mines (Golden)	2.98
20	Franklin and Marshall College (Lancaster, PA)	2.84
21	Princeton University (Princeton, NJ)	2.84
22	University of Arizona (Tucson)	2.80
23	University of Minnesota (Twin Cities)	2.80
24	Indiana University (Bloomington)	2.53
25	University of Rochester (Rochester, NY)	2.51

TABLE AII. Institutional PhD yield ratio. Total number of undergraduates going on to earn geoscience PhD degrees during the years 1966–2011 normalized by undergraduate enrollment.

Rank	Institution	Doctorates/Year/Thousand Undergraduates
1	Carleton College (Northfield, MN)	2.05
2	California Institute of Technology (Pasadena)	1.51
3	Franklin and Marshall College (Lancaster, PA)	1.31
4	Amherst College (Amherst, MA)	1.12
5	Pomona College (Claremont, CA)	0.97
6	Beloit College (Beloit, WI)	0.90
7	Colorado College (Colorado Springs)	0.85
8	New Mexico Institute of Mining and Technology (Socorro, NM)	0.80
9	Colgate University (Hamilton, NY)	0.74
10	University of Montana (Missoula)	0.74
11	Williams College (Williamstown, MA)	0.73
12	Harvey Mudd College (Claremont, CA)	0.70
13	Earlham College (Richmond, IN)	0.61
14	Oberlin College (Oberlin, OH)	0.61
15	Dartmouth College (Hanover, NH)	0.60
16	Colorado School of Mines (Golden)	0.58
17	Hamilton College (Clinton, NY)	0.57
18	St. Lawrence University (Canton, NY)	0.53
19	Haverford College (Haverford, PA)	0.50
20	Occidental College (Los Angeles, CA)	0.49
21	Juniata College (Huntingdon, PA)	0.48
22	Whitman College (Walla Walla, WA)	0.48
23	Allegheny College (Meadville, PA)	0.48
24	Macalester College (St. Paul, MN)	0.47
25	Cornell College (Mt. Vernon, IA)	0.41