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Framing Geologic Numeracy for the Purpose of Geoscience Education: The Geoscience Quantitative Preparation Survey

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DEDICATION

This work is dedicated to Shannon, Luisa, and Josephine Ricchezza, who show me every day the most important things in life.
ACKNOWLEDGMENTS

This project is the culmination of a graduate education done in unusual fashion for unusual reasons. None of it would have taken place but for the interest, patience, assistance, and support of my family, friends, fellow students, professors, and committee. Rob Parks provided the advice I needed coming in and lit the way forward. Lis Gallant, Christine Downs, Matt Hayes, Meghan Cook, Anita Marshall, and Cassandra Smith have been tremendous in their help and support. Jen Bright, Chuck Connor, and Matt Pasek were helpful and kind instructors to work for and resources in this process. Mark Rains, Eric Riggs, and Julie Libarkin have been kind and generous to me as long as I’ve known them. The survey described in this dissertation would not have come together without the expert team of Jen Wenner, Heather Houlton, and especially Jeff Raker, who gave extensively of his time, expertise, and deep knowledge of Disney. The moral and financial support of Jeff Ryan has kept my ideas promoted and my belly full, and I can’t hope to know half as many things in my life as he does. And not one word of this would ever have been written if Len Vacher had not taken a chance and replied to an email from a disgruntled high school science teacher. We’re all lucky to have Len, me most of all.
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ABSTRACT

The Geoscience Quantitative Preparation Survey (GQPS) was developed to address a deficiency in the available literature regarding the competency and preparation of early-career geologists in geoscience job-related quantitative skills – namely, geologic numeracy. The final version of the GQPS included self-confidence, usage, satisfaction, and demographic sections. The GQPS was expected to produce data that would allow for an evaluation of the geologic numeracy of early-career geologists and the success of approximately 20 years of increased focus on quantitatively literate geoscience graduates.

The self-confidence section of the GQPS included quantitative methods and quantitative skills. The usage section asked whether participants used methods or skills from the confidence section in both work and non-work settings. Satisfaction items asked how satisfied participants were with the quantitative preparation they received as undergraduates, relative to career needs, and included items on quantitative problem solving, quantitative communication, and computers. Limited demographic information was collected including time since bachelor’s graduation, years of related experience, undergraduate alma mater, current job status and field, and highest level of education.

Satisfaction values for quantitative problem solving and quantitative communication indicate that respondents were largely satisfied with their undergraduate preparation, with values slightly higher for the geoscience department than for the university as a whole. Satisfaction items related to the use of computers were nearly uniform across all response levels and were not indicative of satisfaction (or any other particular response).
Demographic responses indicate it is reasonable to make some generalizations to the overall population of early-career geologists. Early-career geologists in the sample population showed indications of geologic numeracy. This result indicates the educational trend of the last 20 years of focus on quantitatively literate geoscience graduates has had some success, although this focus cannot be compared to prior years due to lack of data. The GQPS was successful for answering its research questions, but requires validation as a complete scale before it is likely to be used by outside parties.
INTRODUCTION

Existing literature and surveys in the geoscience field indicate that many skills and competencies associated with geologic numeracy are vital to professional success in the geosciences. Extant literature and data on quantitative skills in the geosciences were either collected from students or polled from the opinions of the broader population of geologists, especially those in leadership roles; data from early-career geologists regarding their career-related quantitative literacy and how such data relates to their satisfaction with their undergraduate preparation are deficient. The Geoscience Quantitative Preparation Survey (GQPS) was conceived, developed, and piloted to start to fill this hole.

This dissertation project was based on the following research questions:

1. To what extent are early-career geologists satisfied with the quantitative career preparation they received from their undergraduate geoscience programs?
2. To what extent are early-career geologists geologically numerate relative to the demands of their careers?
3. Will the GQPS be usable for the evaluation of geologic numeracy in early-career researchers by third-party researchers at the conclusion of this study, and what modifications, if any, might be required to make it so?
4. Has instruction in the past two decades (of renewed interest in geologically numerate graduates) provided appropriate preparation for post-graduate work (both career and graduate work)?
The second and fourth of these questions deals with the concept of geologic numeracy (Vacher 2012). Geologic numeracy, Vacher states, includes five dimensions of numeracy plus at least a sixth of basic geologic knowledge.

Figure 1 shows a conception of the scope of this dissertation, envisioned as a tetrahedron. Numeracy, in the context of Figure 1 and this dissertation, is used in the broadest sense of the term, and refers to skills and habits of mind requiring the use of quantitative skills in real world contexts. Undergraduate satisfaction refers in this case to the satisfaction that early-career geologists have with the undergraduate quantitative preparation they received relative to their professional needs. Workplace competence refers specifically to competence in geoscience-related occupations. Geologic knowledge and skills means just that – skills and knowledge related to geology.

In viewing the tetrahedron in Figure 1, attention should be paid to the triangular face between numeracy, geologic knowledge and skills, and (geologic) workplace competence. This triangle represents geologic numeracy in the context of this dissertation.
Figure 1, Tetrahedron illustrating the scope of this dissertation. Figure made by E. Gallant for this dissertation, modified by V. Ricchezza.
FRAMING GEOLOGIC NUMERACY

The term geologic numeracy was introduced by Vacher (2012) as *geological* numeracy, being essentially the intersection of geologic content knowledge and the skills and habits of mind associated with numeracy. First, I will discuss the term numeracy and related terms quantitative literacy and quantitative reasoning. Then, having given some explanation to these terms, I will explain geologic numeracy in greater detail and frame it in the context of this dissertation.

**Numeracy, Quantitative Literacy, and Quantitative Reasoning**

This dissertation deals with concepts associated with the interdisciplinary field of numeracy, among other things. Numeracy is sometimes used interchangeably with related terms *quantitative literacy (QL)* and *quantitative reasoning (QR)* (Vacher 2014). The term *numeracy* was introduced in a report to the British government (Crowther 1959), and numeracy is still the primary broad term used in Commonwealth countries to describe functional fluency with mathematical operations, reasoning, and communication. In the US, the prevailing term is QL. *Mathematics and Democracy* defined that certain elements were included in QL, such as confidence with mathematics, cultural appreciation, interpreting data, logical thinking, making decisions, mathematics in context, number sense, practical skills, prerequisite skills, symbol sense, and confidence in modern communication (Steen 2001). QL is elsewhere described as “the ability to understand and use quantitative measures and inferences that allow one to function as a responsible citizen, productive worker, and discerning consumer” (Madison 2002, p. 1).

Unlike mathematics, which is abstract by its nature, QL is rich in context (Madison 2001). QL is a type of literacy (Daniele 1993); literacy has many levels (Powell 1977), and
QL/numeracy must also have levels (Vacher 2012). In some cases, the levels within QR/QL/numeracy are outlined by the terms themselves, with a great deal of variation among users (Karaali, Villafane Hernandez, and Taylor 2016). The role of educating for QL is cross-disciplinary (Madison 2009). As an example of the hierarchical arrangement found in the literature review of Karaali and associates (2016), the term QR was often used for higher-order thinking, and this thinking was used recently to frame a college algebra sequence with noted success at teaching to high learning outcomes (Piercey 2017).

Figure 2 shows the Vacher model for numeracy definitions as a triangular diagram with the relationship between the terms numeracy (*sensu stricto*), quantitative reasoning (QR), quantitative literacy (QL), and numeracy (*sensu lato*). In Figure 1, numeracy (*sensu lato*) – translated from Latin loosely as “in the broad sense” – is used as a blanket term to cover other uses of terminology in the figure. QL covers the ability to communicate using numbers and quantities, graphs, tables, and other quantitative materials. Numeracy (*sensu stricto*) – loosely translated as “in the strict sense” – indicates an ability to perform mathematical calculations in context. QR is used to indicate the ability to think critically and create mental models for quantitative processes. Unless noted otherwise, where the term numeracy is used in this dissertation it refers to numeracy (*sensu lato*). Vacher’s numeracy triangle (Fig. 2) is based on his interpretation of Vacher (2014), Karaali et al. (2016), and Piercey (2017).

**Geologic Numeracy**

An important part of the transition from novice learner to expert geoscientist is the ability to think quantitatively (Kastens et al. 2018). Educating for geologic numeracy would be different than for numeracy in other fields, as geoscientists think differently (Kastens et al. 2009) and about different things. Geologic numeracy is by nature interdisciplinary; I am concerned
specifically with the application of the ideas behind numeracy as applied to geologists. Vacher (2012) defines geologic numeracy (under the term “geological” numeracy) as the intersection of numeracy and geologic knowledge and skills.

Figure 2, Vacher model of numeracy definitions.

Vacher (2012) outlines five dimensions for numeracy; the sixth dimension for geologic numeracy is geologic concepts and skills. He outlines the five numeracy dimensions as follows (p. 2):

1. Number and other abstractions such as geometric figures, sets, vectors, and matrices; relations and functions; orders of magnitude (logarithms) and directions (angles and
trigonometric ratios); and propositions (statements that have truth value).

2. Operations including not only the familiar arithmetic operations on numbers (addition, multiplications, raising to a power, etc.) but also similar operations on sets, vectors, matrices, and functions, as well as propositions (i.e., logic).

3. Quantities (numbers with units attached) resulting from counting and measuring in the real world. (…)

4. Words (vocabulary) and, more generally, the language, graphs, and metaphors (models) that allow us to make connections between numbers and meaning as well as communicate with each other. (…)

5. Inquiry and problem solving. (…)

Each of these five numeracy dimensions was used as the basis of determining the geologic numeracy of the participants of the GQPS (see “Discussion”). The sixth dimension – geologic knowledge and skills – was inferred to be present in anyone who had a bachelor’s degree in geology and at least three years of related experience (see “Design of the GQPS”).

A Twenty-Year Trend

The Geoscience Education Research (GER) community has had a continued and sustained interest in producing geology graduates with quantitative skills and habits of mind since at least 2000. A special theme issue of the Journal of Geoscience Education in September 2000 was summarized by an editorial (by the co-editors of the issue) titled “Building the
Quantitative Skills of Students in Geoscience Courses”¹ (Macdonald, Srogi, and Stracher 2000). This issue included 17 articles all dedicated to teaching quantitative material in the geosciences, including the article about a then-new course in geologic numeracy at the University of South Florida (Vacher 2000).

After the 2000 JGE special issue, observers may note a focus in geoscience literature and instructional sites on quantitative materials and a goal of quantitatively skilled geology students (and thus graduates). A search for the word “quantitative” on the National Association of Geoscience Teachers (NAGT, the parent organization of the JGE) found 225 matches.² Of these matches, 82 were publications, 31 listed as professional development, 29 as teaching resources, and 40 as news. While some of the publications deal with ‘quantitative’ in the sense that they use quantitative analysis methods on the data they collected (e.g., survey data), many deal with students’ quantitative skills. Additionally, the teaching resources items and some of the professional development items nearly all deal with student quantitative skills and habits of mind.

A similar search for the word “quantitative” on the Science Education Resource Center (SERC) yielded 8999 results, with 2676 classified under “geoscience.” As SERC opened operations in 2001, all of these results are relevant in support of the premise that over the last 20 years the geoscience education community has had geologic numeracy of graduates as one of its goals.

A GER Grand Challenges Workshop, was convened by SERC and the NAGT and funded by the National Science Foundation, in the summer of 2016. The collaborative workshop led to a

² NAGT Search https://nagt.org/nagt/search_nagt.html?search_text=quantitative&search=Go
white paper with 48 contributing authors who identified 10 primary grand challenges facing GER (St. John 2018). One of the 10 grand challenges was “quantitative reasoning, problem solving, and the use of models” (Kastens et al. 2018).
DESIGN OF THE GQPS

Ensuring that future geoscientists are geologically numerate requires deliberate focus in undergraduate geoscience curricula on the intersections of numeracy, workplace competency, and geoscience preparation (St. John 2018). Yet there is currently no significant measure of how geoscience programs are making any changes to their curricula. Thus the GQPS was designed to explore these three constructs – numeracy, geoscience workplace competence, and geological preparation. In order to address geologic numeracy in early-career geoscientists, the GQPS relied on four main resources for its development: Social Cognitive Career Theory (theoretical framework), other numeracy surveys (measures of self-efficacy, use, and satisfaction), the Computational Geology course at USF, and prior workplace competency surveys.

Theoretical Framework

The theoretical framework chosen for this dissertation study was Social Cognitive Career Theory (SCCT) (Lent, Brown, and Hackett 1994). SCCT is based on the prior Social Cognitive Theory (Bandura 1986), but taking the general view of Bandura’s theory into a specific setting and viewpoint related to careers. SCCT was not used rigorously, in the sense of testing a model, but rather was used to inform my thinking in developing the GQPS. SCCT was selected after generation of research questions but before item generation. Considered retrospectively, it would also be reasonable to view the GQPS through the lens of Career Self-Efficacy Theory (Hackett and Betz 1981). In a recent editorial (Betz and Hackett 2006), the two authors of Career Self-Efficacy Theory discuss the relations of their theory to the closely related SCCT, and they discuss how both theories flow from the earlier work of Bandura.
The primary aspects of SCCT are the development of career interests, educational and career planning, and measures of success in career goals (Lent et al. 2008). The SCCT aspects are measured through self-efficacy and satisfaction (Lent and Brown 2008). The portions of the SCCT that are germane to the GQPS are self-efficacy – in this case a proxy measure of self-confidence in quantitative skills was used – and affective satisfaction with pre-set goals. Affective satisfaction versus pre-set goals was measured on the GQPS using satisfaction items related to expectations set during undergraduate education.

Self-efficacy is “a cognitive appraisal or judgment of future performance capabilities,” and it must be put in context with some behavior (Betz and Hackett 2006, p. 6). In the GQPS, self-confidence was used as a proxy for self-efficacy.

**QL Surveys and Assessments**

I performed a search for QL assessment instruments before writing the GQPS. This subsection summarizes the results of that search and analysis and places the results in the context of the dissertation. Many assessments which I located were proprietary, such as the Graduate Record Examination (GRE) owned by ETS. The majority of the located assessments which were not proprietary were associated with the medical field. Table 1 shows a selection of QL assessment instruments that are open access.

**The Lipkus Objective Numeracy Scale**

Of the items listed in Table 1, two are highlighted here because they present a path toward the GQPS. The Lipkus scale (Lipkus, Samsa, and Rimer 2001) involved a short series of actual calculations in a medical/patient context that would be given to prospective medical patients (e.g., a question would tell how many milligrams of a medication were to be taken at what interval, with separate information on the size of each pill and how many in each bottle,
asking the patient to discuss when they would need to order a refill). The Lipkus test was based on, and included, an earlier three-question test that was also named for its primary author (Schwartz et al. 1997). While the Lipkus scale was generally well received in the literature, some difficulties were noted. Primary among these difficulties was that some patients do not want to perform mathematical tasks and refused to participate (Fagerlin et al. 2007).

Table 1, Selection of QL assessment instruments with open access.

<table>
<thead>
<tr>
<th>Assessment Name</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schwartz</td>
<td>Objective measure</td>
</tr>
<tr>
<td>Lipkus</td>
<td>Objective measure</td>
</tr>
<tr>
<td>Subjective Numeracy Scale (SNS)</td>
<td>Subjective self-assessment</td>
</tr>
<tr>
<td>Medical Data Interpretation Test (MDIT)</td>
<td>Objective measure</td>
</tr>
<tr>
<td>Quantitative Reasoning for College Science (QuaRCS)</td>
<td>Objective measure and survey</td>
</tr>
<tr>
<td>Mathematics Attitude Survey</td>
<td>Survey</td>
</tr>
<tr>
<td>Quantitative Literacy Assessment Rubric (QLAR)</td>
<td>Rubric</td>
</tr>
<tr>
<td>Diabetes Numeracy Test (DNT)</td>
<td>Objective measure</td>
</tr>
<tr>
<td>Asthma Numeracy Questionnaire</td>
<td>Objective measure</td>
</tr>
<tr>
<td>Trends in International Math and Science Studies (TIMSS)</td>
<td>Objective measure</td>
</tr>
<tr>
<td>Programme for International Student Assessment (PISA)</td>
<td>Objective measure</td>
</tr>
<tr>
<td>National Survey of Student Engagement (NSSE)</td>
<td>Survey</td>
</tr>
<tr>
<td>SSAC – Wetzel</td>
<td>Objective measure and survey</td>
</tr>
<tr>
<td>SSAC – Lehto</td>
<td>Objective measure and survey</td>
</tr>
<tr>
<td>Miami U QLA</td>
<td>Objective measure</td>
</tr>
<tr>
<td>Michigan State U QLA</td>
<td>Objective measure</td>
</tr>
<tr>
<td>Carleton College Quantitative Reasoning Rubric</td>
<td>Rubric</td>
</tr>
</tbody>
</table>

The Subjective Numeracy Scale

The difficulty noted in implementing the Lipkus scale was taken into account for a new assessment known as the Subjective Numeracy Scale (SNS), which was structured quite differently from the Lipkus scale (Fagerlin et al. 2007). The SNS was developed to help medical professionals determine the numeracy – put simply, the functional quantitative skills – of their patients. The SNS avoided the math-avoidance pitfall encountered by Lipkus by having
participants respond to items regarding their quantitative self-confidence, such as “I am good at working with fractions,” reasoning that a math-avoidant person may still be willing to discuss their fear of math, or perceived weakness in its usage, provided they are not required to perform mathematical calculations (Fagerlin et al. 2007). All items were six-point Likert-style.

Fagerlin et al. (2007) found a close association ($r = 0.68$) with the Lipkus scale for participants taking both assessments. They also measured stress, annoyance, frustration, and willingness to complete another instrument for both the SNS and the Lipkus scale. They found less annoyance, stress, and frustration, and far greater willingness to complete an additional instrument for participants who had taken the SNS. The validity of using the SNS – as opposed to more performance-based assessments – was evaluated by a team associated partially with writing the assessment (Zikmund-Fisher et al. 2007). Zigmund-Fisher and associates tested over 2000 people across three studies where participants completed the SNS and then completed some objective test of quantitative ability, and the predictive ability for the SNS approached that observed for objective numeracy. A copy of the SNS is included in Figure 3. The concept behind the SNS fundamentally inspired the confidence portion of the GQPS.

**On the Merit of Self-Assessment**

There is a natural concern raised whenever participants self-assess their abilities. How do we know that these participants are giving an accurate depiction of their abilities? Are they being truthful? Do they even know their true ability? The “Dunning-Kruger Effect” (Kruger and Dunning 1999, Dunning 2011) stipulates that as novices begin to learn about a topic, they become rapidly confident about their knowledge. A second phase of understanding occurs where learners begin to appreciate the vast amount of knowledge that is possible in a topic, leading to
Cognitive abilities (1 = not at all good, 6 = extremely good)
How good are you at working with fractions?
How good are you at working with percentages?
How good are you at calculating a 15% tip?
How good are you at figuring out how much a shirt will cost if it is 25% off?

Preference for display of numeric information
When reading the newspaper, how helpful do you find tables and graphs that are parts of a story?* (1 = not at all, 6 = extremely)
When people tell you the chance of something happening, do you prefer that they use words (“it rarely happens”) or numbers (“there’s a 1% chance”)?* (1 = always prefer words, 6 = always prefer numbers)
When you hear a weather forecast, do you prefer predictions using percentages (e.g., “there will be a 20% chance of rain today”) or predictions using only words (e.g., “there is a small chance of rain today”)? (1 = always prefer percentages, 6 = always prefer words; reverse coded)
How often do you find numerical information to be useful? (1 = never, 6 = very often)

Figure 3. Subjective Numeracy Scale items. From Fagerlin et al. (2007). Used with permission.

A recent Numeracy study indicated that this Dunning-Kruger effect could be replicated by random noise (Nuhfer et al. 2016). A second study by the same authors noted the Dunning-Kruger effect is overstated if not outright nonexistent (Nuhfer et al. 2017). In the second study, approximately 1200 participants were tested on their science concept knowledge using the Science Literacy Concept Inventory while also assessing their self-confidence. Results indicated that across ability levels, participants accurately assessed their own abilities to within about 5
ppt. of the true value, with women being more likely than men to accurately self-report. This finding was in contrast to prior literature suggesting that women rate themselves lower than their actual level of ability (Beyer, Rynes, and Haller 2004).

One possible explanation for the difference noted between the well-cited studies of Dunning and Kruger and the more recent work of Nuhfer and associates may lie in where the participants in each study lie in the spectrum from novice to expert. In Chapter 4 of How Learning Works (Ambrose et al. 2010), stages of this spectrum from novice to expert are described as unconscious incompetence, conscious incompetence, conscious competence, and unconscious competence. Phrased differently, true novices are incompetent at a given subject or task, and are unaware of the level of their incompetence because they know so little about what there is to know. The next phase is conscious incompetence, where they learn a bit about what there is to learn and come to realize their own ignorance. As they continue to learn, they reach conscious competence where they are entering mastery; they have competence in a skill or content but must think about what they are doing to exercise it. In reaching full mastery or unconscious competence, they use their expert skills and knowledge without having to think about it.

Applying this concept to the Dunning-Kruger and the Nuhfer and associates studies, the groups being tested may simply be at different levels of expertise. In applying the concepts from Ambrose and associates to the GQPS, the population to be studied is not novices, although they may not be considered full experts. At the very least, a geologist with a bachelor’s degree and some post-graduate work experience is likely to be aware of the depth of available knowledge and skill in the domain of geologic numeracy.
Geologic Numeracy at USF

The University of South Florida (USF) Department/School of Geosciences has a long history (early 1990s-present) of teaching for geologic numeracy, which has included the basis for most of my prior published work. My prior work has indicated a possible positive affect and effect for students/alumni of the USF Geology Department/School of Geosciences from a long-standing course in geologic numeracy called Computational Geology. Further study, including quantitative work, was recommended. The GQPS was developed and implemented in part to address the need for quantitative information in relation to USF’s geologic numeracy program, which is described below.

The History of Computational Geology at USF

Since 1996, Dr. H.L. “Len” Vacher (hereafter, LV) has taught an undergraduate course in geologic numeracy at the University of South Florida (USF) named “Computational Geology” with a goal of teaching geological-mathematical problem solving (Vacher 2000). The topics and practices of the Computational Geology course, when discussed and described in this dissertation, refer either to those sections taught by LV or to topics and practices common to all sections.

LV and I undertook a review of the course and its success at reaching learning objectives which resulted in a major change to the course structure. In the summer of 2015, based on a reading of Cognitive Load Theory (Chandler and Sweller 1991, Kirschner, Sweller, and Clark 2006, Sweller 1988, Sweller, Ayres, and Kalyuga 2011, Sweller, van Merrienboer, and Paas 1998), LV and I made major redesigns to the instructional methods of the course. Cognitive Load Theory (CLT) states that the human mind can remember items in either temporary storage (cognitive memory) or long-term storage (permanent memory) (Sweller, Ayres, and Kalyuga
Experts and novices, as end members of a continuum of problem solvers, approach problem solving differently, with experts having committed more content knowledge to permanent memory, and having learned schemas – specific heuristics for coping with familiar scenarios – and committed these to permanent memory as well (Sweller 1988). Novices, having less experience with content and with problem solving, must use mostly cognitive memory when attempting to solve a new type of problem in the context of their domain of study. Literature indicates that while the permanent memory is vast in its storage capacity (Sweller, van Merrienboer, and Paas 1998), the cognitive memory can only reliably hold seven to ten items at a time (Miller 1956). To move along the pathway from total novice closer to expert status (become fluent, perhaps), a learner must encounter multiple problems and learn how to solve them. In so doing they will develop schemas that they commit to permanent memory, which will help if they later encounter a similar situation or problem (Kirschner, Sweller, and Clark 2006). Learners need guided, worked examples, and unguided practice (Chandler and Sweller 1991). Although worked examples were present in earlier sections of Computational Geology, students were getting insufficient amounts of practice working the types of problems introduced in the course. The course redesign attempted to solve this by introducing a series of ten problem sets (Ricchezza and Vacher 2018). Table 2 shows the problem set topics from the Fall 2018 semester of Computational Geology.

Alumni Narratives on Computational Geology

I conducted a study on alumni of the Computational Geology course “Alumni Narratives on Computational Geology (Spring 1997 – Fall 2013)” as my master’s thesis (Ricchezza 2016). The results of the Alumni Narratives study informed the current project, in part. In the Alumni Narratives study, I interviewed ten course alumni who had taken and passed Computational
Geology between the years of 1997 and 2013 and gone on to career success. Participants in the Alumni Narratives study generally described the Computational Geology course as fundamental to their professional development.

Table 2, Problem set topics in Computational Geology.

<table>
<thead>
<tr>
<th>Problem Set</th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Counting/Number Sense</td>
</tr>
<tr>
<td>2</td>
<td>Units and Unit Conversion</td>
</tr>
<tr>
<td>3</td>
<td>Proportions and Percentages</td>
</tr>
<tr>
<td>4</td>
<td>Sums and Averages</td>
</tr>
<tr>
<td>5</td>
<td>Ratios and Rates</td>
</tr>
<tr>
<td>6</td>
<td>Estimation and Error</td>
</tr>
<tr>
<td>7</td>
<td>Circles and Angles</td>
</tr>
<tr>
<td>8</td>
<td>Logarithms and Log Scales</td>
</tr>
<tr>
<td>9</td>
<td>Lines and Planes</td>
</tr>
<tr>
<td>10</td>
<td>Modeling Functions</td>
</tr>
</tbody>
</table>

One question did remain after the Alumni Narrative project concluded: is the USF curriculum (including Computational Geology) any more or less successful at imparting quantitative skills and habits of mind compared to other methods, programs, or national or regional averages? There were no data collected in the Alumni Narratives project that could answer this question. This lack of data was part of the reason the GQPS was considered and conceived.

Existing Workplace Surveys in the Geosciences

The geosciences, and geology specifically, include a wide variety of subtopics for study and professions one can enter (Wilson 2016). All of these subdisciplines and professions, to some degree, include quantitative material (Manduca et al. 2008). A significant portion of the burden in educating geoscience students for QL rests with instructors in introductory university geoscience courses (Wenner et al. 2009). This said, earth science instructors at all levels must
contribute to reach systematic change in quantitative skills for geoscience graduates (Macdonald, Srogi, and Stracher 2000).

While preparing students for a career is hardly the only purpose of an undergraduate education (Axelrod, Anisef, and Lin 2001), a workforce supply gap is present in the geosciences that is expected to increase in the coming years (Houlton 2015). This section presents a selection of recent meetings and studies that addressed the topics of geoscience workforce preparation and meeting workforce needs. These items are included because they show some relevance to the GQPS.

**Geoscience Education Summits**

In 2014, a network of geoscience department heads and chairs met for the first Summit on the Future of Undergraduate Geoscience Education (Mosher et al. 2014). The original summit was followed by a survey which asked respondents from a variety of geoscience backgrounds and occupations to rate the career-based importance of various skills and competencies (Mosher 2015, 2016). Additional summits have followed the original; work by this group, the American Geophysical Union Heads and Chairs Network, is ongoing.

Following the first Summit, a web-based Geoscience Community Survey was released, asking participants a variety of questions including what skills were relevant to a successful career in the geosciences. The results of the summit survey helped inform the GQPS. The summit survey received 455 complete responses across a variety of job categories, e.g., government, academic, private sector (Mosher 2015). The survey’s primary finding was that 80% of participants across different job categories felt that necessary skills and competencies were more important than taking specific courses. Additionally, specific skills and competencies were noted as being of particular high value to employers, with problem solving,
communication, and quantitative skills among the highest rated (Mosher 2015); Figure 4 is from informational conference presentations made by Sharon Mosher, and Figure 5 is from the Summit Survey Report (Mosher 2015).

The Summit Survey identified a series of general geoscience and professional skills and competencies that respondents to that survey felt to be of importance for geoscience education. Several of these skills and competencies are overlapping with QL and would be within the realm of geologic numeracy. These skills include critical thinking/problem solving skills; effectively communicating with scientists and non-scientists; work with uncertainty, non-uniqueness, incompleteness, ambiguity, and indirect observations; have strong quantitative skills and ability to apply them; have strong computational skills and the ability to manage and analyze large datasets.

**AGI Career Master’s Preparation Survey**

The American Geosciences Institute (AGI) conducted an NSF-funded survey of terminal master’s programs in the geosciences in 2013 and 2014 (Houlton 2015). AGI’s Career Master’s
Survey was intended to fill a gap in the literature regarding advanced degree skills and competencies for graduate students in terminal master’s programs who would likely end up in industry. The survey was extensive and queried demographics, background, reasons for entering geosciences, influences on career goals, financial support, satisfaction with departments, post-graduation employment, and technical and non-technical skills proficiencies. The survey was for both geology and geography departments but in most cases results for the two fields were given separately.

*Figure 5, Critical professional and geoscience skills from the Summit Community Survey. Taken from Mosher (2015). Used with permission.*
A specific portion of the Career Master’s survey that was most germane to this dissertation was the portion dealing with technical and non-technical skills for geology. In this section, students and faculty were asked to rate the students’ perceived ability with each skill competency. Separately, a population of industry professionals was asked to rate how important each such skill was, so that the students and faculty to could be compared to the professionally rated expectations. All items were 5-point Likert-style and included an “NA/I don’t know” option. Just over 350 student participants met the criteria for inclusion.3

AGI compared the responses of geology industry professionals to students and professors, and in some cases, such as non-technical skills including problem solving, critical thinking, and quantitative skills, a disparity was clear (Houlton 2015). This disparity implied a gap between the skill level of the survey population and the needs of the profession. Similar deficits were found in several technical skills, where students did not self-assess their skills to the same standing that industry professionals suggested. In contrast, students and professors rated students’ very highly in some skills, such as interpreting fossil assemblages, that were rated as being lower in importance by industry professionals, but Figure 6, taken directly from AGI Geoscience Currents #101 (Houlton and Ricci 2015), shows gaps between student self-confidence and professionals’ ratings of importance and for five non-technical, workplace skills. The research is thorough and provides context for the current dissertation, with “computer & tech” and “critical thinking” being most applicable.

3 For full statistical information on the AGI Career Master’s Survey, see https://www.americangeosciences.org/sites/default/files/hrh/AGI_GCMaPS_StatsResults_ALL_PDF.pdf
Expert Consultation

The process of building and implementing the GQPS involved a team of experts. This section outlines the steps involved in moving from ideas in the SNS to the GQPS. The structure of the SNS is different from that of the related portion of the GQPS; the SNS is only a thematic inspiration for the GQPS rather than a structural blueprint. The process broke down into three phases: (1) expert review and survey changes, (2) pilot testing with graduate students, followed by final changes as needed, and (3) public implementation via anonymous access to an online platform (Qualtrics).

First, I identified a team of survey experts who would participate in a review process. As part of the process, I revised the GQPS survey based on feedback from the expert panel, and then
I sent the revised survey to the expert panel for review. Any panel members available made commentary on changes, and the survey would be changed. I repeated the process until the entire panel agreed with the items. All members of the panel participated in the review process, and all approved the final (pre-testing) document; for individual changes, participation of the panel members depended on availability.

Early during expert review was when the SNS items – which concentrate on specific types of numeracy that would be applicable to the safe use of medicine according to directions – were replaced with items asking about self-confidence that related to geologic numeracy. The selection of specific topics was based on the problem set themes in use in the fall cohort of course GLY 3866: Computational Geology in the USF School of Geosciences (Table 2).

In discussion with experts I determined that the items 3.1-3.5 of the GQPS asked participants how confident they were in solving mathematical problems with the use of certain supports, like calculators or spreadsheets. These first five confidence items deal with quantitative methods. The remaining eleven items of GQPS confidence section are about confidence in specific quantitative skills, such as the ability to correctly use and interpret percentages or logarithms. This distinction between methods and skills was of note later when analyzing results.

One problem that was noted during expert review was that participants were asked how confident they were in their ability to use quantitative skills (like applying map scale), but it was not clear from the item or response whether this ability was necessary at their job. Two separate sets of items were added where respondents were asked whether they used each of the associated skills from the confidence section in work settings and non-work settings. This new section allowed for measurements related to workplace competence, as I would know whether participants used skills at work. After the GQPS administration was completed, I realized that
one item that had been removed from the confidence section during graduate student review on averages had remained in the usage section. Additionally, the wording of one usage item on fractions did not precisely match the wording of the corresponding item in the self-confidence section on percentages.

The next section of the GQPS focused on the degree to which participants were satisfied with the preparation they received as undergraduates. This section relates back to Figure 1, specifically the corner of the tetrahedron of the same name (undergraduate satisfaction), and also the numeracy and geologic knowledge and skills corners. This section was written specifically because of the affective career expectations component of SCCT (Lent, Brown, and Hackett 1994). This satisfaction section in the GQPS consisted of two parallel item sets. The first set asked three satisfaction items related to their undergraduate geoscience program, i.e., courses taken directly from the department, and the second set asked the same three items related to coursework taken as an undergraduate outside of the geoscience department, e.g., calculus course taken from the mathematics department. The three items asked respondents to rate their satisfaction with their undergraduate education with respect to (a) quantitative problem solving skills, (b) quantitative communication skills, and (c) quantitative computer skills.

The final section of the GQPS asked demographic information. To avoid the collection of identifying information or asking items that may be sensitive to some potential respondents, demographic items were severely limited in scope. Respondents were asked how many years ago they received their bachelor’s degree in geology; how many years of related experience, which could include graduate school, they have since that degree; where they received their bachelor’s degree; whether they still work in the geosciences; and what category their job falls into. I used AGI’s job classification categories for the item on current employment (Table 3).
Table 3, AGI job classification categories.

<table>
<thead>
<tr>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-year college</td>
</tr>
<tr>
<td>4-year institution</td>
</tr>
<tr>
<td>Accommodation/food service</td>
</tr>
<tr>
<td>Agriculture/forestry/fishing</td>
</tr>
<tr>
<td>Arts/entertainment/recreation</td>
</tr>
<tr>
<td>Construction</td>
</tr>
<tr>
<td>Environmental services</td>
</tr>
<tr>
<td>Health care/social assistance</td>
</tr>
<tr>
<td>Information services</td>
</tr>
<tr>
<td>Information technology</td>
</tr>
<tr>
<td>K-12 education</td>
</tr>
<tr>
<td>Federal government</td>
</tr>
<tr>
<td>Finance</td>
</tr>
<tr>
<td>Manufacturing or trade</td>
</tr>
<tr>
<td>Mining</td>
</tr>
<tr>
<td>Nonprofit/NGO</td>
</tr>
<tr>
<td>Oil &amp; gas</td>
</tr>
<tr>
<td>Other educational services</td>
</tr>
<tr>
<td>Real estate</td>
</tr>
<tr>
<td>Research institute</td>
</tr>
<tr>
<td>State/local/tribal government</td>
</tr>
<tr>
<td>Transportation</td>
</tr>
<tr>
<td>Utilities</td>
</tr>
<tr>
<td>Other</td>
</tr>
</tbody>
</table>

Pilot Testing

A pilot version of the survey was administered to ten graduate students after the expert panel and I were in agreement regarding the items. Volunteers, where feasible, took the survey on my lab computer, talking to me throughout the process; eight of ten students completed the survey this way. Volunteers were instructed to discuss whatever they felt was important, but to make special note of anything unclear or confusing. While they completed the survey and

---

4 9 of the 10 grad student testers were USF graduate students, however, only 3 completed their bachelor’s degrees at USF.
discussed their thoughts; I took notes. No recordings were made. Two students who lived outside the area took the survey on their own computers and sent me written notes.

The volunteers completed a draft version of the GQPS, and their responses are not included in the main survey data. Changes were not made to any of the questions until all volunteers had completed their participation, to ensure they saw the same survey. Changes made to the survey after piloting were minor. A confidence question about using different kinds of averages was removed as most volunteers found it confusing. Volunteers were alternatively confused by the terms significant figures or digits so where possible both terms were used.

Validity and Reliability

The purpose of the expert panel review and editing followed by piloting with graduate student volunteers was to establish content validity for the GQPS. Through the efforts of the experts on the panel and the ten graduate students, items that were confusing or did not measure what they were intended to measure were revised where possible or removed where necessary. The panel review and pilot testing established content validity by having multiple additional persons, including topic experts, verify that the items on the GQPS were asking what they were designed to measure (Foxcroft et al. 2004).

Measuring reliability in single-item measures is not practical, but the decision whether to use the items should be based on their appropriateness for the concept being measured (Wanous, Reichers, and Hudy 1997). In the case of the GQPS, the expert review panel agreed on the appropriateness of the survey items to measure the concepts of the survey.

Final Survey Form

Tables 4a through 4h show the final wording of the GQPS as made public. Participants were required to answer yes to item 1 (consent) before these items would appear; answering no
would send the participant to the end of the survey and thank them for their time. Item numbers indicate the page of the draft survey on which they appeared. For example, item 4.2 was the second item on page 4 of the survey. Due to editing of the draft document, there was no page/item 2 in the final version. Item 17 would appear only if “other” was selected for Item 16. All items were forced-answer items; the platform would not permit the respondent to move on unless an answer was selected.

Table 4a, Item 1, consent.

<table>
<thead>
<tr>
<th>Item</th>
<th>Text</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Welcome to the research study! We are interested in understanding how geoscientists receive career preparation as undergraduates. You will be presented with information relevant to quantitative preparation of geoscientists and asked to answer some questions about it. Please be assured that your responses will be kept completely confidential. This study is approved by the University of South Florida (USF) Institutional Review Board (IRB) on approval number e35492. Your responses are anonymous. The study should take you around 8 minutes to complete. Your participation in this research is voluntary. You have the right to withdraw at any point during the study, for any reason, and without any prejudice. If you would like to contact the Principal Investigator in the study to discuss this research, please e-mail <a href="mailto:ricchezza@mail.usf.edu">ricchezza@mail.usf.edu</a> to reach Victor J. Ricchezza. By clicking the button below, you acknowledge that your participation in the study is voluntary, you are 18 years of age, and that you are aware that you may choose to terminate your participation in the study at any time and for any reason. Please note that this survey will be best displayed on a laptop or desktop computer. Some features may be less compatible for use on a mobile device. Note: you may receive invitations to this survey from multiple sources (e.g., alumni group, professional society, outside organization). Please complete this survey only once.</td>
</tr>
</tbody>
</table>

Distribution

A script describing the consent procedure was attached to all recruitment emails, and the survey itself had a consent page which required that participants give affirmative consent to
proceed to the survey. Consent email script is included in Appendix C, and the text of item 1 is in Table 4a.

**Table 4b, Confidence items (1a).**

<table>
<thead>
<tr>
<th>Item</th>
<th><strong>Please rate how confident you are in your ability to:</strong></th>
<th><strong>Type/Options</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Perform simple mathematical tasks (like basic arithmetic) in your head (mental math).</td>
<td>Likert/5</td>
</tr>
<tr>
<td>3.2</td>
<td>Perform mathematical tasks like arithmetic without a calculator or equivalent device (pencil-and-paper math).</td>
<td>Likert/5</td>
</tr>
<tr>
<td>3.3</td>
<td>Use calculators (or equivalent) to solve mathematical problems.</td>
<td>Likert/5</td>
</tr>
<tr>
<td>3.4</td>
<td>Use spreadsheets to solve mathematical problems.</td>
<td>Likert/5</td>
</tr>
<tr>
<td>3.5</td>
<td>Create a computer problem to solve a mathematical problem (e.g., using SPSS, PYTHON, R, MATLAB, etc.)</td>
<td>Likert/5</td>
</tr>
<tr>
<td>4.1</td>
<td>Perform unit conversions (such as miles to kilometers or liters to gallons) if given conversion factors and calculator or equivalent.</td>
<td>Likert/5</td>
</tr>
<tr>
<td>4.2</td>
<td>Read, calculate, and explain percentages.</td>
<td>Likert/5</td>
</tr>
<tr>
<td>4.3</td>
<td>Work with proportions such as fractions or map scale to solve problems.</td>
<td>Likert/5</td>
</tr>
<tr>
<td>4.4</td>
<td>Solve problems using ratios, such as the Pythagorean theorem or vertical exaggeration.</td>
<td>Likert/5</td>
</tr>
<tr>
<td>5.1</td>
<td>Estimate error in measurements and calculations (first-order or “ballpark” estimate).</td>
<td>Likert/5</td>
</tr>
<tr>
<td>5.2</td>
<td>Work with the proper number of significant figures/digits in calculations.</td>
<td>Likert/5</td>
</tr>
<tr>
<td>5.3</td>
<td>Use basic trigonometry to find unknown values (e.g., height of an unknown building, if given distance away on level ground and angle to top of building).</td>
<td>Likert/5</td>
</tr>
<tr>
<td>6.1</td>
<td>Work with logarithms.</td>
<td>Likert/5</td>
</tr>
<tr>
<td>6.2</td>
<td>Read or report information on a logarithmic scale or graphical axis.</td>
<td>Likert/5</td>
</tr>
<tr>
<td>6.3</td>
<td>Solve problems using linear/matrix algebra.</td>
<td>Likert/5</td>
</tr>
<tr>
<td>6.4</td>
<td>Estimate the probability of an event occurring, if given the necessary background information.</td>
<td>Likert/5</td>
</tr>
</tbody>
</table>

**Table 4c, Response choices for confidence items.**

<table>
<thead>
<tr>
<th>Response Choices For Confidence Items</th>
<th>Assigned Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not at all confident</td>
<td>1</td>
</tr>
<tr>
<td>Slightly confident</td>
<td>2</td>
</tr>
<tr>
<td>Moderately confident</td>
<td>3</td>
</tr>
<tr>
<td>Very confident</td>
<td>4</td>
</tr>
<tr>
<td>Extremely confident</td>
<td>5</td>
</tr>
</tbody>
</table>
Table 4d, Work and non-work setting usage items, (1b).

<table>
<thead>
<tr>
<th>Item</th>
<th>Please indicate whether you use each type of math skill or habit of mind in WORK/NON-WORK SETTINGS.</th>
<th>Type/Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1/8.1</td>
<td>Mental math</td>
<td>Yes/No</td>
</tr>
<tr>
<td>7.2/8.2</td>
<td>Pencil-and-paper math</td>
<td>Yes/No</td>
</tr>
<tr>
<td>7.3/8.3</td>
<td>Calculator math</td>
<td>Yes/No</td>
</tr>
<tr>
<td>7.4/8.4</td>
<td>Spreadsheet math</td>
<td>Yes/No</td>
</tr>
<tr>
<td>7.5/8.5</td>
<td>Programming for math</td>
<td>Yes/No</td>
</tr>
<tr>
<td>7.6/8.6</td>
<td>Unit conversions</td>
<td>Yes/No</td>
</tr>
<tr>
<td>7.7/8.7</td>
<td>Fractions</td>
<td>Yes/No</td>
</tr>
<tr>
<td>7.8/8.8</td>
<td>Proportions</td>
<td>Yes/No</td>
</tr>
<tr>
<td>7.9/8.9</td>
<td>Averages</td>
<td>Yes/No</td>
</tr>
<tr>
<td>7.10/8.10</td>
<td>Ratios</td>
<td>Yes/No</td>
</tr>
<tr>
<td>7.11/8.11</td>
<td>Estimating error</td>
<td>Yes/No</td>
</tr>
<tr>
<td>7.12/8.12</td>
<td>Significant digits</td>
<td>Yes/No</td>
</tr>
<tr>
<td>7.13/8.13</td>
<td>Trigonometry</td>
<td>Yes/No</td>
</tr>
<tr>
<td>7.14/8.14</td>
<td>Logarithms</td>
<td>Yes/No</td>
</tr>
<tr>
<td>7.15/8.15</td>
<td>Logarithmic scales/axes</td>
<td>Yes/No</td>
</tr>
<tr>
<td>7.16/8.16</td>
<td>Matrix algebra</td>
<td>Yes/No</td>
</tr>
<tr>
<td>7.17/8.17</td>
<td>Estimating probability</td>
<td>Yes/No</td>
</tr>
</tbody>
</table>

Table 4e, Satisfaction items, departmental (2).

<table>
<thead>
<tr>
<th>Item</th>
<th>Please rate your agreement regarding your undergraduate geoscience program (i.e., coursework, research, and learning specific to the geoscience department at the major level, not other coursework at your university, or any work afterward).</th>
<th>Type/Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.1</td>
<td>My undergraduate geoscience program gave me the quantitative problem solving skills I need for professional success.</td>
<td>Likert/5</td>
</tr>
<tr>
<td>9.2</td>
<td>My undergraduate geoscience program gave me the quantitative communication skills (ability to read and write about quantitative material in both text and illustrations) I need for professional success.</td>
<td>Likert/5</td>
</tr>
<tr>
<td>9.3</td>
<td>My undergraduate geoscience program gave me the computer skills I need for professional success.</td>
<td>Likert/5</td>
</tr>
</tbody>
</table>

It became clear early in the collection process that locating potential participants was going to be difficult. The initial idea of collecting data using a more formal, traditional approach (send email requests to a known number of persons, calculate a response rate based on the
number of surveys received) was quickly discarded. The core problem was identified: early-career geologists are very hard to locate and contact. Students are relatively easy to locate, as they generally have a school-issued email account. Established, later-career professionals are somewhat easy to locate, as they can be reached through alumni societies, professional groups, etc., but early-career geologists fell into a middle ground. Even the professionals at AGI – who send surveys of this type frequently – were at a loss regarding how to generate a list of early-career individuals.

Table 4f, Satisfaction items, university (2).

<table>
<thead>
<tr>
<th>Item</th>
<th>Please rate your agreement regarding your overall undergraduate program outside of the geoscience program (i.e., coursework, research, and learning offered by any department other than the geoscience department, even if required for degree completion, not including graduate or other work done after undergraduate degree completion).</th>
<th>Type/Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.1</td>
<td>The non-geoscience courses from my undergraduate program gave me the quantitative problem solving skills I need for professional success.</td>
<td>Likert/5</td>
</tr>
<tr>
<td>10.2</td>
<td>The non-geoscience courses from my undergraduate program gave me the quantitative communication skills (ability to read and write about quantitative material in both text and illustrations) I need for professional success.</td>
<td>Likert/5</td>
</tr>
<tr>
<td>10.3</td>
<td>The non-geoscience courses from my undergraduate program gave me the computer skills I need for professional success.</td>
<td>Likert/5</td>
</tr>
</tbody>
</table>

Table 4g, Response choices for satisfaction items.

<table>
<thead>
<tr>
<th>Response Choice For Satisfaction Items</th>
<th>Assigned Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strongly disagree</td>
<td>1</td>
</tr>
<tr>
<td>Somewhat disagree</td>
<td>2</td>
</tr>
<tr>
<td>Neither agree nor disagree</td>
<td>3</td>
</tr>
<tr>
<td>Somewhat agree</td>
<td>4</td>
</tr>
<tr>
<td>Strongly agree</td>
<td>5</td>
</tr>
</tbody>
</table>
Table 4h, Demographic items (3).

<table>
<thead>
<tr>
<th>Item</th>
<th>Text</th>
<th>Type/Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>What is your highest completed level of education?</td>
<td>BA/BS&lt;br&gt;Some graduate coursework&lt;br&gt;Graduate certificate&lt;br&gt;Masters&lt;br&gt;Doctorate</td>
</tr>
<tr>
<td>12</td>
<td>What is the name of the college or university where you completed your BA/BS in geology?</td>
<td>Text entry</td>
</tr>
<tr>
<td>13</td>
<td>How many years of professional experience/preparation do you have after earning your BS/BA in geology (rounded to the nearest whole number)? (Graduate school may be counted as experience, as may anything where your BA/BS in geology was necessary or useful. Degrees in earth science, geochemistry, or geophysics count as &quot;geology&quot; for the purposes of this survey.)</td>
<td>Dropdown (integer values from 0-50)</td>
</tr>
<tr>
<td>14</td>
<td>How many years has it been since you graduated with your bachelor's degree? (Please round to the nearest whole number.)</td>
<td>Dropdown (integer values from 0-50)</td>
</tr>
<tr>
<td>15</td>
<td>Do you currently work in the geosciences?</td>
<td>Yes/No</td>
</tr>
<tr>
<td>16</td>
<td>Which of these best describes your job category?</td>
<td>Dropdown (AGI list)</td>
</tr>
<tr>
<td>17</td>
<td>Other occupation type:</td>
<td>Text entry (only appears if “other” selected for 16).</td>
</tr>
</tbody>
</table>

A short series of email lists was sent – I counted 92 emails sent directly from me:

- I sent an email to any fellow USF faculty and graduate school classmates with the request that they take the survey if within the target range, and send it to anyone from their undergraduate institution who was appropriate.

- AGI sent the email to a list of scholarship applicants who had previously applied for an unrelated award. This list had fewer than 250 names.

- I sent the email to the USF Geology Alumni Society board members, who circulated it individually in their respective organizations where they deemed it appropriate.
As it rapidly became obvious I would be unable to track the number of requests sent out from secondary parties, I ceased any coordinated attempt to do so and expanded my recruitment efforts to include social media, mainly via Twitter and Facebook. Twitter proved the simplest for this purpose as anyone could “retweet” a request for participation (i.e., send out someone else’s post on to their own followers). Multiple high-profile geologists and geology departments helped in this effort, which is greatly appreciated. Facebook was more useful in group pages. During the last ten days of the survey, I went to the Geological Society of America annual meeting in Indianapolis with 500 business cards printed with a QR code and a URL for the survey site. Figure 7 shows an image of the business card used for final recruiting. The Michigan State University Geocognition Research Laboratory set out the cards on their display tables while collecting their own surveys.

![Early Career Geologists Needed for Survey](image)

**Early Career Geologists Needed for Survey**
USF IRB 35492, Principal Investigator Victor J. Ricchezza
ricchezza@mail.usf.edu

**Do You Have:**
BS or BA in Geology, earned 3-10 years ago?
3-7 years of related experience? (can include grad school)

If so, visit the link below or scan the QR code to access.
Takes 10 minutes, totally anonymous!
https://usf.az1.qualtrics.com/jfe/form/SV_8oZBsNE4koxUa9f

*Figure 7, Recruiting card used at 2018 GSA national meeting.*
This recruitment can be described as snowball sampling (Baltar and Brunet 2012). In snowball sampling, respondents recruit additional participants, which causes the number of participants to “snowball” in size. This approach has the advantage of increasing the overall size of the sample, but it has some disadvantages. The number of requests sent is not known, as they did not all originate with me, and the impacts of open-ended requests such as those on social media are impossible to measure.

The GQPS link went live on the Qualtrics® platform on August 20, 2018. The survey was suspended on November 30, 2018.

**Descriptive Statistics**

The confidence and satisfaction items on the GQPS use Likert-style responses (Likert 1932), where a declarative statement is made (e.g., I am confident I can…), followed by a series of choices allowing respondents to rate their level of confidence or agreement (DeVellis 2016). In the case of the GQPS, all confidence and satisfaction items are asked on a five-point Likert-style answer set. Refer to Table 4c for confidence answer choices and Table 4g for satisfaction answer choices. Although no numbers were associated with the choices on the actual survey, in Table 5 and Figures 9a and 9b I use numerical values. *Extremely confident* and *strongly agree* are classified as 5; *not at all confident* or *strongly disagree* are classified as 1; intermediate numbers correspond to answers in Table 4c and 4g. Confidence and satisfaction data are treated as ranked-order/ordinal (Göb, McCollin, and Ramalhoto 2007), and the preferred measure of central tendency is the median (Sheskin 2003).
RESULTS

Figures 8-10 and Tables 5-8 show the results from surveys collected from the target set – i.e., the filtered data set containing only complete responses from 178 participants who met the early-career criteria. Data are presented primarily as data tables and frequency histogram plots showing the percentage of each response using numerical Likert responses (1-5) rather than text (see Table 4b for correlation of numbers and response text).

Raw Information Totals

In total, 377 completed surveys were received. Most (53%) of the surveys received were actually outside the preferred “early-career” range desired. Unless specifically noted, all discussion of sample results from this point is in reference to the Target sample.

Data clean up included date and time the survey was started and finished, Internet Protocol (IP) address of respondent, total survey time, and consent responses, as none of these were relevant to data analysis. Initial cleanup and some table work were done in Microsoft Excel. The cleaned raw data were imported into RStudio (a free open-source computer code interface using the R programming language), version 1.1.463. The version of R used was 3.5.1. All other statistical analysis and graphics were done in RStudio. Later editing of data was also done in Microsoft Excel.

General Distributions

In this section, I present the results for confidence, work usage, and undergraduate satisfaction sections of GQPS. Table 5 presents the percentage of responses within each of the five Likert categories, the percentage of responses within the two top categories, the median
value, and the item topic. The maximum response value for all items was 5; minimum values were 1 except where red highlights were visible in Table 5.

**Table 5, Percentage distribution of responses, target dataset.** Grey highlights indicate items with values of 4 and 5 combined to exceed 50% of total responses. Gold highlights indicate median response for that item. Red highlights indicate item/response combinations with no responses.

<table>
<thead>
<tr>
<th>Item</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>&gt;3</th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>0%</td>
<td>5%</td>
<td>25%</td>
<td>31%</td>
<td>38%</td>
<td>70%</td>
<td>Mental math</td>
</tr>
<tr>
<td>3.2</td>
<td>0%</td>
<td>2%</td>
<td>23%</td>
<td>44%</td>
<td>30%</td>
<td>75%</td>
<td>Pencil-paper math</td>
</tr>
<tr>
<td>3.3</td>
<td>0%</td>
<td>0%</td>
<td>10%</td>
<td>31%</td>
<td>59%</td>
<td>90%</td>
<td>Calculator math</td>
</tr>
<tr>
<td>3.4</td>
<td>2%</td>
<td>3%</td>
<td>15%</td>
<td>28%</td>
<td>51%</td>
<td>79%</td>
<td>Spreadsheet math</td>
</tr>
<tr>
<td>3.5</td>
<td>39%</td>
<td>30%</td>
<td>11%</td>
<td>15%</td>
<td>6%</td>
<td>20%</td>
<td>Programming math</td>
</tr>
<tr>
<td>4.1</td>
<td>0%</td>
<td>1%</td>
<td>6%</td>
<td>39%</td>
<td>54%</td>
<td>93%</td>
<td>Unit conversions</td>
</tr>
<tr>
<td>4.2</td>
<td>0%</td>
<td>2%</td>
<td>9%</td>
<td>24%</td>
<td>65%</td>
<td>89%</td>
<td>Percentages</td>
</tr>
<tr>
<td>4.3</td>
<td>0%</td>
<td>3%</td>
<td>14%</td>
<td>37%</td>
<td>47%</td>
<td>83%</td>
<td>Proportions</td>
</tr>
<tr>
<td>4.4</td>
<td>0%</td>
<td>6%</td>
<td>16%</td>
<td>35%</td>
<td>43%</td>
<td>78%</td>
<td>Ratios</td>
</tr>
<tr>
<td>5.1</td>
<td>4%</td>
<td>11%</td>
<td>35%</td>
<td>33%</td>
<td>16%</td>
<td>49%</td>
<td>Estimating error</td>
</tr>
<tr>
<td>5.2</td>
<td>3%</td>
<td>8%</td>
<td>19%</td>
<td>44%</td>
<td>25%</td>
<td>70%</td>
<td>Significant digits</td>
</tr>
<tr>
<td>5.3</td>
<td>4%</td>
<td>7%</td>
<td>24%</td>
<td>27%</td>
<td>38%</td>
<td>65%</td>
<td>Trigonometry</td>
</tr>
<tr>
<td>6.1</td>
<td>13%</td>
<td>22%</td>
<td>35%</td>
<td>21%</td>
<td>9%</td>
<td>30%</td>
<td>Logarithms</td>
</tr>
<tr>
<td>6.2</td>
<td>11%</td>
<td>14%</td>
<td>21%</td>
<td>27%</td>
<td>27%</td>
<td>54%</td>
<td>Logarithmic scales/axes</td>
</tr>
<tr>
<td>6.3</td>
<td>25%</td>
<td>28%</td>
<td>20%</td>
<td>17%</td>
<td>9%</td>
<td>26%</td>
<td>Matrix algebra</td>
</tr>
<tr>
<td>6.4</td>
<td>6%</td>
<td>23%</td>
<td>38%</td>
<td>26%</td>
<td>8%</td>
<td>34%</td>
<td>Estimating probability</td>
</tr>
<tr>
<td>9.1</td>
<td>3%</td>
<td>13%</td>
<td>6%</td>
<td>49%</td>
<td>29%</td>
<td>78%</td>
<td>Department – quantitative problem solving</td>
</tr>
<tr>
<td>9.2</td>
<td>3%</td>
<td>9%</td>
<td>6%</td>
<td>42%</td>
<td>40%</td>
<td>81%</td>
<td>Department – quantitative communication</td>
</tr>
<tr>
<td>9.3</td>
<td>14%</td>
<td>27%</td>
<td>16%</td>
<td>24%</td>
<td>19%</td>
<td>43%</td>
<td>Department – computers</td>
</tr>
<tr>
<td>10.1</td>
<td>4%</td>
<td>9%</td>
<td>19%</td>
<td>41%</td>
<td>26%</td>
<td>67%</td>
<td>University – quantitative problem solving</td>
</tr>
<tr>
<td>10.2</td>
<td>6%</td>
<td>11%</td>
<td>13%</td>
<td>43%</td>
<td>26%</td>
<td>69%</td>
<td>University – quantitative communication</td>
</tr>
<tr>
<td>10.3</td>
<td>16%</td>
<td>21%</td>
<td>21%</td>
<td>28%</td>
<td>13%</td>
<td>41%</td>
<td>University – computers</td>
</tr>
</tbody>
</table>

**Quantitative Methods Confidence Distributions**

The first confidence section (3.1-3.5) included five items relating to respondents’ confidence about quantitative methods; for items 3.1-3.4, the majority of respondents chose “very confident” (a value of 4) or “extremely confident” (a value of 5; Table 5) with medians of “very confident” (4) for 3.1-3.2 and “extremely confident” (5; Table 5) for 3.3-3.4. For items 3.1.3.3, no respondents chose “not at all confident” (a value of 1; Table 5). Responses to item
3.5 are dominated by values that denote lower confidence in computer programming with a median of “slightly confident” (a value of 2).

Quantitative Skills Confidence Distributions

The second confidence section (4.1-6.4) included eleven items relating to respondents’ confidence in using quantitative skills; for items 4.1-4.4, 5.2-5.3, and 6.2, the majority of respondents chose “very confident” (4) or “extremely confident” (5; Table 5) with medians of “very confident” (4) for 4.3-4.4, 5.2-5.3, and 6.2 and “extremely confident” (5; Table 5) for 4.1-4.2. For items 4.1.-4.4, no respondents chose “not at all confident” (1; Table 5). Median responses to items 5.1, 6.1, and 6.4 were “moderately confident” (3, Table 5) Responses to item 6.3 are dominated by values that denote lower confidence in matrix algebra with a median of “slightly confident” (2, Table 5).

Satisfaction Distributions

The satisfaction section (9.1-10.3, Table 5) included six items in two parallel sets of three related to participants’ satisfaction with undergraduate preparation at the departmental (9.1-9.3) and university (10.1-10.3) levels. For items 9.1-9.2 and 10.1-10.2, the majority of respondents chose “slightly agree” (4) or “strongly agree” (5, Table 5) with median values of “slightly agree” (4) for all four items. Satisfaction in quantitative problem solving (9.1 and 10.1) and quantitative communication (9.2 and 10.2) indicated slightly higher satisfaction for geoscience department coursework than coursework outside the department. Items 9.3 and 10.3, both of which relate to satisfaction with computer preparation, have median values of “neither agree nor disagree” (3, Table 5) and have distributions which are nearly evenly balanced between agreement and disagreement (Table 5.) Satisfaction between department and university level coursework was similar (43% vs 41% combined 4 and 5 values for 9.3 and 10.3 respectively, Table 5).
Career Usage Comparison Distributions

This section presents results of items on usage of quantitative methods and skills in work and non-work settings (Fig. 8) and comparisons of confidence responses for those answering yes to work usage versus those answering no (Fig. 9a and 9b). Such comparison is only made for confidence items.

Use of Quantitative Skills in Work and Non-Work Settings

Figure 8 shows percentage of yes responses for each part of items 7 and 8. Values for use outside of work settings at or above 69% indicated that mental math, pencil-and-paper math, calculator math, spreadsheet math, unit conversions, fractions, proportions, averages, and ratios are all quantitative methods or skills used in the daily life of the participants. A majority of participants said they also used estimating error, significant digits, trigonometry, and logarithmic scales/axes at work. The number of participants saying they used a method or skill at work but not outside of work was notable for programming math, estimating error, significant digits, trigonometry, logarithms, logarithmic scales, and matrix algebra. Values for estimating probability were similar for both work and non-work. Items marked with an asterisk also had a median value of moderately confident (3) or lower in the corresponding confidence item, and this low median value is noted to occur in items whose use in work settings was at or below 40% - programming for math, logarithms, linear algebra, and estimating probability – with one exception, estimating error (59% work usage). Likewise for those items with a greater than 50% usage in work settings, only estimating error had a median value (3) below very confident (4, Table 5).
Figure 8, Percentage answering yes to items 7 and 8. † Fewer participants responded yes to the at work item than the out of work item. *median responses were 3 or lower.

Split Histograms

Figures 9a and 9b show split histograms for all confidence items. For each of the confidence items, the distribution is split into two bars in different colors. The blue bar represents respondents who answered yes on the corresponding section of item 7 for use in work settings; the orange bar is for those who answered no. On the y-axis is the confidence score.
Figure 9a, Split histograms for items 3.1 through 5.3.
(ranging from 5: extremely confident, to 1: not at all confident); on the x-axis is the total number of responses.

![Split histograms for items 6.1 through 6.4. Fewer participants responded yes to the at work item than the out of work item. Median responses were 3 or lower.](image)

**Figure 9b, Split histograms for items 6.1 through 6.4.** Fewer participants responded yes to the at work item than the out of work item. Median responses were 3 or lower.

**Demographic Responses**

Table 6 shows the responses to item 11, which asked the highest level of education completed. Five options were given, but no responses were received for “Graduate Certificate.” Both “bachelors” and “some graduate” would be considered bachelors for degree purposes, meaning 39% of participants had a bachelor’s degree at the time of survey completion.

Table 7 summarizes the responses to Item 12, which asked participants what university they got their geology BA/BS from. Response was via text entry box. Responses are only shown for those universities with two or more alumni. The remaining 52% of responses to Item 12 were single-entries.

Figure 10 shows the results of Item 15, which asked whether participants were currently working in the geosciences. As noted in the figure, 88% of respondents are currently working in the geoscience field. Although 12% of respondents did indicate that they were not currently...
working in the geosciences, it is important to remember that all of these values are for participants with 3-7 years of geoscience-related experience. So even though these people may not be working in the geosciences now, they have recent experience that is relevant to this dissertation, and their continued inclusion is not accidental.

Table 6, Results of Item 11, highest education level of participants.

<table>
<thead>
<tr>
<th>Level</th>
<th>Count</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bachelors</td>
<td>43</td>
<td>24%</td>
</tr>
<tr>
<td>Some Graduate</td>
<td>27</td>
<td>15%</td>
</tr>
<tr>
<td>Masters</td>
<td>94</td>
<td>53%</td>
</tr>
<tr>
<td>Doctorate</td>
<td>14</td>
<td>8%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>178</strong></td>
<td><strong>100%</strong></td>
</tr>
</tbody>
</table>

Table 7, Responses to Item 12.

<table>
<thead>
<tr>
<th>University</th>
<th>Count</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Western Washington University</td>
<td>13</td>
<td>7.3%</td>
</tr>
<tr>
<td>University of South Florida</td>
<td>11</td>
<td>6.2%</td>
</tr>
<tr>
<td>University of Florida</td>
<td>7</td>
<td>3.9%</td>
</tr>
<tr>
<td>Whitman College</td>
<td>5</td>
<td>2.8%</td>
</tr>
<tr>
<td>University of Wisconsin-River Falls</td>
<td>5</td>
<td>2.8%</td>
</tr>
<tr>
<td>Eastern Washington University</td>
<td>5</td>
<td>2.8%</td>
</tr>
<tr>
<td>University of West Georgia</td>
<td>4</td>
<td>2.2%</td>
</tr>
<tr>
<td>University of Arkansas</td>
<td>4</td>
<td>2.2%</td>
</tr>
<tr>
<td>James Madison University</td>
<td>3</td>
<td>1.7%</td>
</tr>
<tr>
<td>Allegheny College</td>
<td>3</td>
<td>1.7%</td>
</tr>
<tr>
<td>University of Wisconsin-Eau Claire</td>
<td>2</td>
<td>1.1%</td>
</tr>
<tr>
<td>University at Buffalo</td>
<td>2</td>
<td>1.1%</td>
</tr>
<tr>
<td>University of North Carolina at Chapel Hill</td>
<td>2</td>
<td>1.1%</td>
</tr>
<tr>
<td>Concord University</td>
<td>2</td>
<td>1.1%</td>
</tr>
<tr>
<td>University of Colorado</td>
<td>2</td>
<td>1.1%</td>
</tr>
<tr>
<td>University of British Columbia</td>
<td>2</td>
<td>1.1%</td>
</tr>
<tr>
<td>McGill University</td>
<td>2</td>
<td>1.1%</td>
</tr>
<tr>
<td>Amherst College</td>
<td>2</td>
<td>1.1%</td>
</tr>
<tr>
<td>Colorado School of Mines</td>
<td>2</td>
<td>1.1%</td>
</tr>
<tr>
<td>St. Lawrence University</td>
<td>2</td>
<td>1.1%</td>
</tr>
<tr>
<td>Brown University</td>
<td>2</td>
<td>1.1%</td>
</tr>
<tr>
<td>State University of New York at Oswego</td>
<td>2</td>
<td>1.1%</td>
</tr>
<tr>
<td>Washington State University</td>
<td>2</td>
<td>1.1%</td>
</tr>
<tr>
<td>Other universities with one alumnus/a</td>
<td>92</td>
<td>51.7%</td>
</tr>
</tbody>
</table>
Figure 10, Results of Item 15.

Table 8 shows the results of Item 16, which asked for the participants’ current field of employment. As noted in Table 3 the categories were the same as those used by AGI.
Table 8, Results of Item 16.

<table>
<thead>
<tr>
<th>Field</th>
<th>Count</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 year college</td>
<td>2</td>
<td>1%</td>
</tr>
<tr>
<td>4 year college</td>
<td>41</td>
<td>23%</td>
</tr>
<tr>
<td>Construction</td>
<td>8</td>
<td>4%</td>
</tr>
<tr>
<td>Environmental Serv.</td>
<td>33</td>
<td>19%</td>
</tr>
<tr>
<td>Federal Gov.</td>
<td>7</td>
<td>4%</td>
</tr>
<tr>
<td>Information Serv.</td>
<td>1</td>
<td>1%</td>
</tr>
<tr>
<td>K12 Education</td>
<td>3</td>
<td>2%</td>
</tr>
<tr>
<td>Manufacturing/Trade</td>
<td>2</td>
<td>1%</td>
</tr>
<tr>
<td>Mining</td>
<td>14</td>
<td>8%</td>
</tr>
<tr>
<td>Nonprofit/NGO</td>
<td>4</td>
<td>2%</td>
</tr>
<tr>
<td>Oil/Gas</td>
<td>11</td>
<td>6%</td>
</tr>
<tr>
<td>&quot;Other&quot;</td>
<td>14</td>
<td>8%</td>
</tr>
<tr>
<td>Other Education</td>
<td>1</td>
<td>1%</td>
</tr>
<tr>
<td>Research Institute</td>
<td>20</td>
<td>11%</td>
</tr>
<tr>
<td>State/Local/Tribal Gov.</td>
<td>17</td>
<td>10%</td>
</tr>
<tr>
<td>Total</td>
<td>178</td>
<td>100%</td>
</tr>
</tbody>
</table>
DISCUSSION

In this section my primary purpose is to evaluate the results of the GQPS by comparing them to: (1) Figure 1, the conceptual tetrahedron of this dissertation’s scope; (2) the four research questions from the Introduction, and (3) Vacher’s five dimensions of numeracy plus the sixth dimension for geologic numeracy, basic geologic knowledge and skills (Vacher 2012). Additional discussion will frame demographic results versus information available regarding the total population of early-career geologists to determine the degree to which it is safe to generalize the GQPS results and conclusions.

Conceptual Tetrahedron

The scope of the dissertation was conceptualized using the tetrahedron in Figure 1. In this section, I frame the results through the lens of the conceptual tetrahedron.

Geologic Knowledge and Skills

One corner of the tetrahedron – geologic knowledge and skills – was assumed to be present as participants had a geology degree and a minimum of three years of geoscience-related experience. Nothing in the GQPS asked participants about geologic concepts or skills.

Undergraduate Satisfaction

The simplest results to evaluate are the satisfaction items related to undergraduate preparation in quantitative problem solving and quantitative communication skills. The trends shown (Table 5, items 9.1, 9.2, 10.1, and 10.2) for satisfaction in these items indicates that the combined strong or slight agreement with the item statement “my [program/university] gave me the [skill] needed…” was at a minimum of 67% for university level and 78% for geoscience
department-specific training. Any judgment of just how much approval is needed to declare overall success is by its nature subjective. That said, more than ¾ of participants indicating at least some satisfaction with their geoscience departments can only be viewed positively.

However, satisfaction with computer skills (Table 5, items 9.3 and 10.3) was much more difficult to interpret. The distributions themselves were essentially uniform – the median values being in the middle (neutral) for both computer items, and the combined dissatisfied values being nearly equal to the combined satisfied values. The question of why remains. During review of the data, it was pointed out that in the confidence section, separate items were present for the use of spreadsheets (3.4) and programming (3.5) to solve quantitative problems, but the satisfaction section only references “computer skills.” The use of spreadsheets is a computer skill, as is programming a computer using more sophisticated coding (e.g., Python). The satisfaction item does not differentiate between the different methods.

Additionally, the percentage of respondents using these two skills in work (and non-work) settings was notably different (Fig. 8). With more than 9 of 10 participants using spreadsheets in work settings, it is not clear if this spreadsheet usage would be in their minds when discussing their undergraduate program’s computer preparation, or whether spreadsheets are so ubiquitous that their use would be taken for granted, and thus the person would be considering programming.

Another grey area was between the computer satisfaction items and the computer skills items. While many geoscientists may not need to program a computer in work settings, it seems likely to me that many geoscientists use computer applications beyond spreadsheets. Just how many geoscientists would need (or have) this particular computer skill I cannot say, as the GQPS includes no items that measure for it.
Numeracy

Looking back to “Framing Geologic Numeracy/Geologic Numeracy,” recall that Vacher (2012) laid out five dimensions of numeracy and added a sixth for geologic numeracy, which was basic geologic knowledge and skills. The geologic content is assumed, and there’s certainly the possibility that this assumption is in error, but the GQPS does not measure geologic content. The five numeracy dimensions are number and other abstractions, operations, quantities, communication, and problem solving.

Communication and problem solving are not measured through confidence questions on the GQPS but are included (twice each) in the satisfaction section as discussed above. Satisfaction items on unit conversions, estimating error, and estimating probability may all fit with the quantities dimension. All of the satisfaction items fit within one or more of the first three dimensions, excepting perhaps items on quantitative methods, as these deal with how, rather than what.

Reviewing what was reported in Table 5, median values and a majority of responses were in the two highest confidence levels for mental math, pencil-and-paper math, calculator math, spreadsheet math, unit conversions, percentages, proportions, ratios, significant figures, trigonometry, and logarithmic scales/axes. Median values were 2 or 3 with a lack of confidence overall in programming math, logarithms, matrix algebra, and estimating probability. Estimating error (median 3, 49% of responses in top 2 categories) was harder to classify.

When compared to their overall usage (Table 5), the distributions of the lower-confidence items (those with median values of 2 or 3 in Table 5) did not significantly improve when only those using the skill at work were considered (Fig. 9a and 9b). Confidence distributions for those who use these particular skills in work settings (Fig. 9a and 9b) still trended toward non-
confidence (programming math, matrix algebra) or neutral/middling confidence (estimating error, logarithms, estimating probability).

For estimating error, logarithms, and estimating probability items, at least 1/3 of the sample population (or much higher) used these at work. A one-in-three chance that a student will need a skill is at least high enough to consider that it is important. Additionally, while only 34% use logarithms, 54% use logarithmic scales; personal experience at instruction tells me that logarithms and logarithmic scales are inextricably linked topics. Error and probability having mediocre confidence distributions may speak to the mathematical curriculum. Each of these items are discussed more frequently in courses on statistics than mathematics, and it is not clear – as it was not included in the GQPS – what coursework respondents took as undergraduates.

The instructional importance of matrix algebra and programming math items is not clear. Only 18% of respondents indicated use of matrix algebra in work settings (Fig. 8). It is therefore unclear whether the poor confidence distribution of matrix algebra is important for instructional purposes. As discussed in earlier material, we do not know what our students will go on to do professionally. If fewer than 1 in 5 of these students will need matrix algebra, the important finding in this area may be the lack of necessity for this skill rather than the confidence level of those few who use it.

Programming for math is more difficult to place in context than the other skills and methods included in the GQPS. Distributions of confidence are poor, and 1/3 of respondents used this skill in a work setting. However, trends over time have led to more computerization of study and workforce uses. It seems a safe assumption – to me – that future geoscientists are at least as likely as current ones to need computer programming skills. Put differently, we know 1 in 3 of our graduates now need this skill, and in general they’re not confident in what they have
in this area; it seems likely that computer programming skills will be at least as important of a focus area, or more so, in the future.

**Workplace Competence**

Workplace competence was not directly measured on the GQPS. However, the satisfaction items were stated as relative to workplace needs (e.g., 9.1: “My undergraduate geoscience program gave me the quantitative problem solving skills I need for professional success.”) Additionally, since any respondent in the target dataset has a minimum of three years of geoscience professional experience, at least a minimal degree of competency was assumed. The experience of these participants was also a factor in the participants knowing what skills, at what level, would be needed for professional success.

**Demographics**

The purpose of this section is to discuss the degree to which the sampled population represents the total population of early-career geologists. This determination is primarily accomplished through comparison of GQPS demographic data to existing published data from AGI.

One question considered was whether to include the responses from the 12% of the target sample that is not currently working in the geosciences (Figure 10). I ultimately decided to keep these responses. Saying that those respondents did not currently work in the geosciences does not mean they had chosen to permanently leave the field; they could be temporarily unemployed or starting a family, for example. Additionally, they did meet the requirement of having 3-7 years of geoscience-related experience; even if that experience was not currently being put to direct use, their knowledge of the requirements of professional geoscience work should still be appropriate for consideration.
Generalizability

Among the primary purposes of performing a quantitative study such as a survey is the generalizability of the results to the wider population (Libarkin and Kurdziel 2002). This goal of generalizability raises a specific concern with respect to the GQPS: to what extent does the sample set represent the general population of early-career geologists. One particular weakness of snowball sampling is difficulty in knowing whether any portion of the population has been oversampled, and so, in the case of this GQPS, other means must be used. For the GQPS, I attempted to show that the sample population was representative of the overall population by comparing demographic information from the target responses to known factors about the overall population with similar qualifying characteristics (i.e., early-career).

Table 6 indicates 39% of GQPS target participants had bachelor’s degrees, 53% had master’s degrees, and 8% have earned doctorates; this breakdown seems reasonable given that a maximum of seven years of related experience (including graduate education) can be included since baccalaureate graduation. Comparing this degree information to information found in AGI Geoscience Currents #131 (Keane 2018) is not inconsistent.

AGI’s information (Keane 2018) shows the total number of bachelor’s, master’s, and doctoral degrees granted in the geosciences (this information is collected across the geosciences, rather than just in geology). Over the time period of the early-career GQPS range, bachelor’s degree awards were between 3,000 and 4,000 annually. Master’s degrees were awarded to 1,000 to 1,500 annually, and doctorates were awarded to about 700-800 annually. It is unclear what percentage of doctoral graduates earned master’s degrees, but I have assumed that all advanced degree holders previously earned a bachelor’s.
Table 9 shows the data previously presented in Table 6 (results of highest level of education on the GQPS) with approximate calculated data from AGI Geoscience Currents #131 (Keane 2018). I have calculated the highest and lowest percentage of graduate degrees out of the total during the GQPS-eligible years (2008-2015). Since the information in AGI’s release is presented in a graph and cannot be read to more than an estimated value, I have rounded all percentages in these estimates to the nearest 5%.

Table 9. Comparison of GQPS participant degree levels with estimated levels from AGI Geoscience Currents #131.

<table>
<thead>
<tr>
<th>Degree</th>
<th>GQPS</th>
<th>AGI (Keane) Min</th>
<th>AGI (Keane) Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bachelor</td>
<td>39%</td>
<td>65%</td>
<td>55%</td>
</tr>
<tr>
<td>Master</td>
<td>53%</td>
<td>25%</td>
<td>30%</td>
</tr>
<tr>
<td>Doctorate</td>
<td>8%</td>
<td>10%</td>
<td>15%</td>
</tr>
</tbody>
</table>

The estimated percentage of bachelor’s degrees in the Table 9 AGI columns varies between 55% and 65%, which is 15 to 25 percentage points higher than the results of the GQPS. The percentage of master’s degrees in the Table 9 AGI estimated columns varies from 25% to 30%, far less than the 53% of the GQPS. However, the percentage of doctorates in the GQPS data is lower than the AGI estimates in Table 9 (8% vs. 10-15%). I conjecture that due to the short time since bachelor’s graduation – less than 7 years of graduate school experience – some portion of the master’s degree graduates in the GQPS data may be doctoral students. Additionally, the GQPS required a minimum of 3 years of experience – which could include graduate school – and the AGI survey makes no such requirement. AGI’s data therefore includes geologists who, due to time constraints, could not possibly have completed a master’s degree (or higher). The percentage of graduate degrees in the GQPS is higher than the AGI data would indicate is likely, and it is unclear why. Once again, the data presented by Keane (2018) is for all of the geosciences, and it is not stated that the percentages of each degree type is consistent.
across sub-fields of the geosciences; I have assumed homogeneity of the geosciences in this respect for the purposes of an estimate only.

A secondary comparison can be made between the primary occupations GQPS participants provided in item 16, “which of these best describes your job category?” which is attached to a pull-down list provided by AGI (see Table 3 for AGI job classifications and Table 8 for results of item 16). In AGI’s report on recent geoscience graduates from 2017 (Wilson 2018), recently hired graduates are broken down by the same job categories, with each degree type charted separately (Wilson 2018, pg. 31). Table 10 compares selected results of the GQPS item 12 to AGI results from the 2017 State of the Workforce Report (Wilson 2018).

Table 10, Comparison of selected GQPS Item 12 results to AGI State of the Workforce 2017 Report results.

<table>
<thead>
<tr>
<th>Category</th>
<th>GQPS</th>
<th>AGI – BA/BS</th>
<th>AGI – MA/MS</th>
<th>AGI - PhD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental services</td>
<td>17%</td>
<td>30%</td>
<td>17%</td>
<td>7%</td>
</tr>
<tr>
<td>4-year university</td>
<td>23%</td>
<td>11%</td>
<td>5%</td>
<td>54%</td>
</tr>
<tr>
<td>Research institute</td>
<td>11%</td>
<td>7%</td>
<td>&lt;1%</td>
<td>31%</td>
</tr>
<tr>
<td>Oil and gas</td>
<td>6%</td>
<td>5%</td>
<td>28%</td>
<td>8%</td>
</tr>
</tbody>
</table>

The GQPS results noted in Table 10 for these four key indicator categories – chosen because they make up a majority of responses for all groups – fall between the values AGI found for bachelor’s and doctoral graduates. Overall, the values from the GQPS target population match many of the same characteristics as the population sampled by AGI, with some differences. The high percentage of master’s graduates in the GQPS doesn’t match the MA/MS oil and gas employment rates, indicating either that this segment of the population was undersampled, or that many of these MS graduates are actually PhD students who obtained a master’s during their graduate education path, but not as a terminal degree.
One other possibility is based on the geographical range of the respondents. Although the GQPS was a web-based survey, and participants had undergraduate degrees from across the United States and Canada, I am based in Florida, as are the second and third most frequent alma maters of GQPS participants (Table 7). Oil and gas are not large industries for geologists in Florida, but environmental services are, and most terminal master’s degrees in geology at USF are for hydrogeology concentrations such as one would use in environmental work or state/local government regulatory work. Table 7 shows that USF (11) and the University of Florida (7) were the second and third most represented, so there is some bias toward Florida programs – about 10% of the target population.

It therefore appears reasonable at this stage to treat the initial GQPS results as representative of the larger population with the significant caveat that the current study is only preliminary testing of and with the GQPS instrument. Further study is recommended and planned using this instrument. When further study occurs, careful attention must be paid to how it will be determined that the sample population is representative of the general population.
CONCLUSIONS

Satisfaction with Undergraduate Quantitative Preparation

One research question for the GQPS was the extent to which early-career geologists were satisfied with the quantitative preparation they received as undergraduates relative to the demands of their careers. These results indicate:

- Most participants are satisfied with the quantitative problem solving and quantitative communication skills they learned at their undergraduate university.
- Most participants are satisfied with both of the above items as taught in their geoscience department and outside the department, but satisfaction levels were higher from department-taught courses.
- Participants’ satisfaction with computer skills learned at their undergraduate university was inconclusive. Median values indicated “neither agree nor disagree” with satisfaction, but the distribution/spread of data is nearly uniform for both department and university-based items. Additionally, the lack of clarity in the item – is it referring to computer usage or programming? – makes interpretation of the results even more problematic. The satisfaction item also asks only about “computer skills,” but does not specify what skills or that they must be quantitative in nature. While it is difficult to draw clear conclusions from these data, it is clear enough that there is significant room for improvement.
Career-Related Quantitative Self-Confidence

Another research question for the GQPS was the extent to which early-career geologists self-identified as geologically numerate. The geologic numeracy of the participants was determined here by comparing the distributions of confidence items and the percentage of respondents who used each skill in work settings.

Framing Geologic Numeracy Relative to Individual Career Usage

The simplest way to assess which skills were relevant to geologic numeracy, while recognizing that not all geoscience careers require the same level or amount of quantitative skill is to look at the career requirements of each participant as unique. The GQPS is a collection of individually validated items and geologic numeracy is a complex construct, so this determination requires a judgment. Rather than viewing a specific set of methods or skills and defining those as being necessary for geologic numeracy, we can simply look at the distributions for each method or skill, looking only at those who said they used that skill in a work setting.

Under these criteria, it is reasonable to say that relative to the demands of their careers the sample population of early-career geologists is geologically numerate. However, room for improvement is apparent. Several items had either mediocre (estimating error, logarithms, estimating probability) or poor (linear/matrix algebra and programming math) confidence distributions.

Geologic Numeracy for Geoscience Education

Another research question was “has instruction in the past two decades (of renewed interest in quantitatively literate geoscience graduates) provided appropriate preparation for post-graduate work (both career and graduate work)?” No baseline information is available on the state of the workforce 20 years ago. All that is apparent is that there has been more interest in
quantitative skills in geology in the last 20 years, and that workforce quantitative skills data are nearly nonexistent. The latter point was among the reasons the GQPS was conceived. Answering this research question is difficult in any objective sense.

This difficulty was addressed through a proxy question “are recent geology graduates geologically numerate?” The answer to the proxy question is “yes,” and the results of the GQPS indicate that early-career geologists possess geologic numeracy sufficient to meet the needs of their jobs.

The Summit Survey (Mosher 2015) indicated that working geologists and academics teaching geology felt that skills and competencies associated with geologic numeracy were vital for graduating geologists, and that learning necessary skills and competencies was more important than taking any specific course. Confidence in computer-related skills varied between the confident distribution of spreadsheet math and the unconfident distribution of programming math. The distribution of satisfaction in computer skills indicated no clear overall success in educating for student satisfaction. The combination of these results raises a question. Do universities lag behind industry in training their students to use computers as tools for geologic numeracy? The GQPS is ill-equipped to answer this type of question.

Future Work

The remaining research question asked whether the GQPS would be usable for the evaluation of geologic numeracy by third-party researchers, and if not, what modifications might be needed to make this possibility. The GQPS was not successfully validated as a scale, although the process used for content validation did establish validity and address the question of reliability for individual items. The answer to the research question is no, in the present form of the GQPS, as an outside researcher would almost certainly want a full scale that is valid and
reliable to work with. The second part of the research question is answered in the broad sense by saying that the GQPS must be validated as a scale.

The GQPS was successful at providing the framework necessary to answer the research questions that were used to design it. However, several issues were either not answered adequately or were raised as new questions based on the survey process or the results of the survey. The following action items are proposed for further research and study.

**Development of Formal Scale for GQPS**

The first proposed additional step in the GQPS project is the adaptation of the GQPS to a formal scale. In a scale, responses to items are added, and the resulting composite score provides for a much larger range of possible scores. Adaptation to a scale allows for the possibility of treating the data as interval or ratio, and of analyzing such data using parametric methods. Such an undertaking may require outside expert consultation and multiple years of work, but would be worthwhile for the data and analysis that would potentially be generated. The GQPS is more likely to be used by outside researchers as a valid, reliable scale.

**Advancement of GQPS beyond Geology**

The GQPS includes “geoscience” in its name, but this label was unintentionally misleading. The initial version of this study was developed based on the topics of a course for teaching QL to geologists. The GQPS was given specifically only to early-career geologists, and not the wider field of geoscience or “the geosciences,” which includes oceanography, atmospheric science, climatology, meteorology, and environmental science. Application of the basic research questions of the GQPS to these populations is merited. Some change to the question topics might be necessary for these audiences, such as inclusion of calculus or
differential equations. These topics, while not part of QL, are mathematical skills that are relevant to certain job groups (atmospheric sciences at a minimum).

There may also be some merit in expanding the GQPS beyond the geosciences altogether to a wider scientific audience. Such a change likely would involve even wider alterations to the survey instrument, including the name itself.

**Identification and Location of Early-career Professionals**

In an ideal setting, the members of a population can be identified, and a random sample of those members can be selected for survey requests. The generalizability of such results to the wider population is much easier to accomplish.

In the case of the initial iteration of the GQPS, such a plan was not possible. Nothing resembling a comprehensive list of early-career geologists was available. Had the intent been to survey students, email address lists are readily available, lacking only permission to access them. It seems reasonable to suggest that professionals later in their careers might be easier to reach than the early-career professionals from this dissertation as they are more likely to have established connections through employers, alumni societies, or professional societies. Finding the early-career cohort, however, is so problematic that solutions are difficult to readily suggest. A separate study is suggested – using either qualitative or mixed methods, possibly including one or more focus groups – to identify the barriers to reaching early-career professionals and suggest solutions.
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APPENDIX A: OTHER PUBLISHED WORKS BY THE AUTHOR
On a Desert Island with Unit Sticks, Continued Fractions and Lagrange

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Available at: http://scholarcommons.usf.edu/numeracy/vol9/iss2/art8

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On a Desert Island with Unit Sticks, Continued Fractions and Lagrange

Abstract
GLY 4866, Computational Geology, provides an opportunity, welcomed by our faculty, to teach quantitative literacy to geology majors at USF. The course continues to evolve although the second author has been teaching it for some 20 years. This paper describes our experiences with a new lab activity that we are developing on the core issue of measurement and units. The activity is inspired by a passage in the 2008 publication of lectures that Joseph Louis Lagrange delivered at the Ecole Normale in 1795. The activity envisions that young scientists are faced with the need to determine the dimensions of a rectangle with no measuring device other than an unruled stick of unknown length – to hundredths of a stick length. Following Lagrange, the students use the stick to measure the lengths with continued fractions, and then they reduce the continued fractions and convert them to decimal form. In the process, these student veterans of calculus instruction learn that as a group they are not very good at the arithmetic of fractions, which they thought they learned in the fifth grade. The group score on a continued fraction item improved from 44% on the pre-course test to 84% on the post-course test in the first semester in which the new lab was included (Fall 2015).

Keywords
measurement, units of measure, quantitative literacy, continued fractions, arithmetic of fractions, measurement error, accuracy vs. precision, geoscience education

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Cover Page Footnote
Vic Ricchezza is a doctoral student at the University of South Florida. He studies the state of quantitative literacy within geoscience education research.
Len Vacher is a professor of geology in the School of Geosciences at the University of South Florida.

This notes is available in Numeracy: http://scholarcommons.usf.edu/numeracy/vol9/iss2/art8
Introduction

The concept of continued fractions has a long and distinguished history. The list in Wikipedia, for example, begins with Euclid’s *Elements* (300 BC)\(^1\) and includes such milestones as John Wallis’s *Opera Mathematica* (1695),\(^2\) which introduced the term; Leonhard Euler’s *De fractionibus continuis dissertatio* (1737)\(^3\) for an account that included the first proof of the irrationality of \(e\); and an application by Johann Lambert that was the first proof of the irrationality of \(\pi\) (1761)\(^4\). However, the question of interest to most impatient scientists—geologists in the case of this paper’s authors and their students—is what practical use can a seemingly esoteric mathematical concept such as continued fractions possibly be to everyday concepts in our own field. For the answer to this question we can turn to the great Joseph Louis Lagrange, another 18th century mathematician.

Specifically, we were drawn to the following passage on the usage of continued fractions in *Lectures in Elementary Mathematics* (Lagrange 1795, 2–3):

… Suppose, for example, that you have a given length, and that you wish to measure it. The unit of measure is given, and you wish to know how many times it is contained in the length. You first lay out the measure as many times as you can on the given length, and that gives you a certain whole number of measures. If there is no remainder, your operation is finished. But if there be a remainder, that remainder is still to be evaluated.…

If you have a remainder, since that is less than the measure, naturally you will seek to find how many times your remainder is contained in this measure. Let us say two times, and a remainder is still left. Lay this remainder on the preceding remainder. Since it is necessarily smaller, it will still be contained a certain number of times in the preceding remainder, say three times, and there will be another remainder or there will not; and so on.…

As former field geologists, we conjure up an image of determining lengths, areas, and volumes while stranded at a field site (such as the proverbial desert island) without a tape measure, or a manufactured measuring device of any kind. What to do? Lagrange and a *unit stick* provide a method and, at the same time, drives home the notion of unit of measure, an everyday concept that underscores the transition from elements in our students’ mathematics classrooms (numbers) to elements in ours on quantitative literacy (quantities, which—for us—are numbers with units).

\(^1\) Ref, e.g., Euclid; Heath (2006).
\(^2\) Ref, e.g., Wallis; Scriba (1972)
\(^3\) See Wyman (1985)
\(^4\) Ref, Lambert (1762)
It is worth noting in passing that Lagrange, of course, is not a random name from the history of mathematics for geologists and geology students. Our students are aware of Lagrange’s role in the creation of the metric system (particularly relevant to our topic of the “unit stick”). In subsequent hydrogeology courses, the students learn the crucial difference between the Eulerian view and the Lagrangian view for conceptualizing fluid flow as a prelude to modeling it. Some of our more fortunate students who continue with their calculus make good use of Lagrange multipliers. His is a name they should recognize and continue to encounter, along with Laplace and Poisson.

At the same time, from our experience with teaching continued fractions in a lab about measurement, we are convinced that nothing is better than continued fractions at ferreting out student inability to manipulate fractions. How dependent they are on their calculators!

**Background**

The verbal description in the quotation from Lagrange translates to the following continued fraction,

\[ 3 + \frac{1}{2 + \frac{1}{3}} \]

assuming that the “unit of measure” of the quotation went into the “given length” three times with a remainder, and ignoring the “and so on.” Using the rules for the arithmetic of fractions, the continued fraction is equivalent to (“reduces to”) 24/7.

This arithmetic was introduced as a learning concept in a laboratory activity in GLY 4866—Computational Geology—at the University of South Florida (USF) in the fall 2015 semester, and then again in the spring semester in an amended version. This note describes the laboratory activity (see Appendix) and the results of our study of it. Student results have been collected from the two semesters and compared ad hoc to show what happened during the implementation of this activity. It should be noted that the study was not conceived as a rigorous educational research project. It was designed as a laboratory activity to assist students in reaching course learning objectives. Data collected were only those that were normal to the educational process.

The methods of the study were submitted to the USF Institutional Review Board (IRB), as required, for approval prior to submission of any papers for publication involving students as subjects. The USFIRB did not consider this work to be research under their purview because all students were required to participate as part of the normal activities of the course.
Method

Students in the fall section of the course were given a pre-course test on the first day of the course, and the test included a continued fraction to reduce/solve. During the semester, as laboratory activity #4, all students participated in a participation-graded lab consisting of a pre-activity quiz followed by the lab activity itself. Students were then given a question on their first midterm exam which, in text form, explained a similar scenario to that found in the lab (very similar to the example given by Lagrange); the exam question asked the students to organize the measurements as a terminated continued fraction (that is, a continuing fraction that is finite in its number of continuations, as opposed to a reduced form of that fraction), and give a decimal equivalent to a certain number of decimal places (credit for the question was solely for the decimal answer). At the last class session before the final exam review, students were given the same pre-course test from the first session of the semester, but as a post-course test.

In the spring semester, the pre- and post-course tests were not used, but the lab was largely similar; the class size was much smaller (27 students in fall versus 8 in spring). The pre-activity quiz was used unchanged in the lab. Students were given a similar test item on their first midterm exam, with separate answer areas for laying out a continued fraction, reducing it, and giving a decimal equivalent. After largely successful results (see discussion of results below) an additional, ratcheted-up test item was included in the second midterm exam. This additional question asked the students to work backward from a reduced fraction to determine the equivalent terminated continued fraction (with numerators all equal to one) and express in words the measurements and remainders that would have produced it.

The pre-activity quiz was a simple, terminated continued fraction that students were asked to “evaluate and solve.” Students were graded for participation (making an attempt, even if they did not know what to do, resulted in points, but students who came late to class and missed the pre-quiz did not receive points). The primary purpose of this pre-activity quiz was to formatively assess student knowledge at the start of the lab activity (as this information would allow the authors/instructors to determine to what level it was necessary to cover or re-cover the skills for reducing the fractions themselves, versus the practical use of the fractions in measurement as used in the lab).

The lab activity itself was relatively simple. Students were organized into small groups and provided with an unruled plastic device—in this case actually a portion of a logarithmic slide rule that was used in a later lab, but without the scale labels—and asked to measure the length and width of their desk using this device. During initial runs of the lab, the length unit was referred to as the “Denis” in honor of Dr. Denis Voytenko, former graduate teaching assistant of the
course, now a postdoctoral fellow at the Center for Atmosphere Ocean Science, Courant Institute of Mathematical Sciences (New York University). Future iterations of this lab will use something such as disposable chopsticks as the measuring device—the previous devices all now have labels for their use as slide rules—and will go by the simple name of “sticks.” For purposes of simplicity in reporting this lab, the units are referred to as sticks and abbreviated “stx”. For example, in terms of the unit stick, the decimal form of the continued fraction in the quotation from Lagrange is 3.43 stx.5,6

Students were asked to provide the length and width of their table—and calculate the area—to the hundredths place. All the tabletops used were of uniform size (for a given semester), as were the measurement devices (the units were produced on the USF campus using a “3D printer” to pre-set measurements of 184 mm length, although students did not know this value at the time of the lab). Fall and spring cohorts met in different classrooms. In other words, the tabletops being measured are different in size across the two semesters, while the “stick” measuring standards were the same. In the initial lab, students were asked to measure each value once. After comparison of student group results (see below), this requirement was modified for the spring semester, and student groups were asked to measure length and width three times each.

In detail, in order to complete the lab properly, students would measure how many times the unit stick measured against the length of the desk. Students would count how many whole times the stick would fit, and then, assuming the number was not evenly divisible—that is, there was a remainder left over, which was indeed the case for all iterations of the lab on the first length and width measurement—they would note the length of this remainder by some means such as a mark on a blank piece of paper. This remainder ($r_1$) was then compared against the length of the stick. The remainder would, much like the original length, fit a certain number of whole times, with perhaps a second remainder ($r_2$). The length of $r_2$ would then be compared to the length of $r_1$—if necessary by marking the length of each on a blank piece of paper to see whether this was evenly divisible, or a third remainder ($r_3$) was present. If so, students would have to compare $r_3$ versus the length of $r_2$, but as this work was all done by hand and without magnification, the limits of human measurement made it unlikely that the process would continue beyond $r_3$ (although theoretically it could continue for quite some time). The results were arranged into a simple continued fraction (that is, a continued fraction where the numerator is always one).

5 Or would 3.4 or 3.429 stx be better? We hardly broached the subject of measurement uncertainty and will develop it further in future iterations of the course.

6 We look forward to word problems involving about kilostx and millistx. We already use word problems involving sq stx.
After measurement, the continued fraction was reduced/solved, and converted to a decimal equivalent (students were permitted to use a calculator for this lab, although prior labs in this course did require pencil-and-paper and mental-only calculation methods to refresh those skills), rounded to the hundredths place. This procedure was then repeated for the width (and in the case of the spring semester version of the lab, it was performed three times for each dimension). Students were also asked to provide error for their values, but they were not provided with written instructions for how to determine error.

Student groups then provided their measurements to the class at large. Measurements were compared against each other. The first author went at a later time and measured the tabletop surface using a standard ruled meter stick to determine the length and width in SI units, which he converted to “sticks” so that a “correct” (Gold Standard) value would be available for comparison. Group values were compared for accuracy and precision to determine whether a hundredths place measurement was practical. In other words, accuracy was measured by determining whether the student-reported value range contained the actual Gold Standard value for the unknowns. Precision was measured by the repeatability of measurements across groups (or in the spring semester, by repeat measurements by the same group), testing whether the measured range was smaller than 0.01 times the base unit, or alternately by how small a range the values or their reported errors included.

Students were later given one question on their first midterm exam in the fall semester and one question on each of the two midterms in spring that re-created the experience of the lab, and thus required them to set up a continued fraction from a text description of the lab measurements, reduce/solve the continued fraction in fraction form, and give a decimal approximation to a certain number of significant figures (the second midterm in spring had students work backwards from the solution to determine the original measurements). Student responses in the fall semester on the continued fraction item from the pre-course test, the lab pre-activity quiz, the first midterm, and the post-course test were compared (as aggregate percentages per class, to protect student privacy) to determine whether, and to what extent, gains were made on the skill/task over the semester. Spring semester students were given a pre-activity quiz and two midterm exam items regarding the skill.

Results

Student Lab Group Responses

Table 1 indicates student responses for the fall semester; there were 27 students total, with one absent on the day of the lab. Table 2 indicates student responses for spring. As students were grouped into groups of up to four for each semester,
there were two groups in the spring (Team Hutton and Team Steno, 8 students total). It is therefore unreasonable to draw any quantitative conclusions from the spring student responses other than to report them.

First, we look at length measurements from Table 1. The length measurement provided by group 8 is a clear outlier, compared to the others. When removed, the mean becomes 8.22 stx and the standard deviation 0.05 stx. This standard deviation indicates a reasonable precision to the tenths place (two significant figures, in this case). However, students were asked to give values to the hundredths place (three significant figures). Clearly the measurements taken using this method did not meet this level of precision. It is possible that repeated measurements would have given more precise figures. The Gold Standard value was obtained using a meter stick and dividing the value by the known length of the stick from its 3D printing programming. The actual value was about 8.23 stx, and the average of the measured lengths was very close to this value if the outlying value for group 8 is removed (8.22 stx). The width measurements had a smaller standard deviation, even when compared to the size of the measurements. The average width (3.22 stx) and the actual value (3.26 stx) varied, but within the standard deviation (0.09 stx). Hundredth place precision is also not indicated for this measurement.

<table>
<thead>
<tr>
<th>GROUP</th>
<th>Length (stx)</th>
<th>+/-</th>
<th>Width (stx)</th>
<th>+/-</th>
<th>Area (stx^2)</th>
<th>+/-</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.20</td>
<td>0.005</td>
<td>3.20</td>
<td>0.005</td>
<td>26.24</td>
<td>0.057</td>
</tr>
<tr>
<td>2</td>
<td>8.32</td>
<td>0.005</td>
<td>3.21</td>
<td>0.005</td>
<td>27.5</td>
<td>0.01</td>
</tr>
<tr>
<td>3</td>
<td>8.21</td>
<td>0.02</td>
<td>3.23</td>
<td>0.02</td>
<td>26.52</td>
<td>0.11</td>
</tr>
<tr>
<td>4</td>
<td>8.25</td>
<td>0.05</td>
<td>3.32</td>
<td>0.050</td>
<td>29.39</td>
<td>0.786</td>
</tr>
<tr>
<td>5</td>
<td>8.167</td>
<td>0.005</td>
<td>3.2</td>
<td>0.05</td>
<td>26.133</td>
<td>0.43</td>
</tr>
<tr>
<td>6</td>
<td>8.17</td>
<td>0.085</td>
<td>3.03</td>
<td>0.015</td>
<td>27.18</td>
<td>0.09</td>
</tr>
<tr>
<td>7</td>
<td>8.24</td>
<td>0.005</td>
<td>3.25</td>
<td>0.005</td>
<td>26.78</td>
<td>0.06</td>
</tr>
<tr>
<td>8</td>
<td>9.2</td>
<td>0.05</td>
<td>3.2</td>
<td>0.05</td>
<td>29.44</td>
<td>0.62</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Mean</th>
<th>Length (stx)</th>
<th>+/-</th>
<th>Width (stx)</th>
<th>+/-</th>
<th>Area (stx^2)</th>
<th>+/-</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.34</td>
<td>0.03</td>
<td>3.22</td>
<td>0.03</td>
<td>27.40</td>
<td>0.27</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 Fall 2015 Student Measurement Data

All measurements and errors are self-reported by student groups, and are shown exactly as provided by the groups. All means, medians, and standard deviations were rounded to the hundredths place for simplicity. N=26

In Table 2 (spring semester) the width measurement for both groups was accurate to the hundredths place (3.22 stx). Length for “Team Steno” was also very closely replicated by repeat measurements, but not so for “Team Hutton.” That team’s length range was accurate (included correct value, 9.95 stx), but unreasonably wide. Given the small number of groups, it is difficult to draw much meaning from these numbers. However, it is quite troubling that Team Hutton failed so profoundly in measuring the table’s length. The first author was

James Hutton (1726–1797) and Nicolas Steno (1638–1686) were important figures in the history of geology—contemporaries of, e.g., Euler (1707–1783) and Leibniz (1646–1716), respectively.
instructing the class during the lab session and was with this group during part of this time. The group appeared to be performing the measurement as one would expect—making a measure, lightly marking the slate table with a pencil, then measuring from there, and so forth. How the team then got values of 11.05, 10.88, and 9.74 stx is befuddling. It did appear that each measurement was made by a different member of the group, and if the 9.74 stx value was a simple blunder, the other two values do at least round to the same integer value, 11 stx.

Table 2  
Spring 2016 Student Measurement Data

<table>
<thead>
<tr>
<th>GROUP</th>
<th>L1 (stx)</th>
<th>L2 (stx)</th>
<th>L3 (stx)</th>
<th>L Avg (stx)</th>
<th>+/-</th>
<th>W1 (stx)</th>
<th>W2 (stx)</th>
<th>W3 (stx)</th>
<th>Avg (stx)</th>
<th>+/-</th>
<th>Area (stx²)</th>
<th>+/-</th>
</tr>
</thead>
<tbody>
<tr>
<td>HUTTON</td>
<td>11.06</td>
<td>10.88</td>
<td>9.74</td>
<td>10.56</td>
<td>1.10</td>
<td>3.25</td>
<td>3.33</td>
<td>3.33</td>
<td>3.30</td>
<td>0.05</td>
<td>34.85</td>
<td>1.78</td>
</tr>
<tr>
<td>STENO</td>
<td>9.14</td>
<td>9.11</td>
<td>9.14</td>
<td>9.13</td>
<td>0.03</td>
<td>3.33</td>
<td>3.33</td>
<td>3.33</td>
<td>3.33</td>
<td>0.00</td>
<td>30.40</td>
<td>0.10</td>
</tr>
<tr>
<td>MEAN</td>
<td>10.10</td>
<td>10.00</td>
<td>9.44</td>
<td>9.85</td>
<td>0.57</td>
<td>3.29</td>
<td>3.33</td>
<td>3.33</td>
<td>3.32</td>
<td>0.03</td>
<td>32.63</td>
<td>0.94</td>
</tr>
<tr>
<td>ST. DEV.</td>
<td>1.36</td>
<td>1.25</td>
<td>0.42</td>
<td>1.01</td>
<td>0.76</td>
<td>0.06</td>
<td>0.00</td>
<td>0.00</td>
<td>0.02</td>
<td>0.04</td>
<td>3.15</td>
<td>1.19</td>
</tr>
</tbody>
</table>

Measurements reported by student groups. Statistics are based on only two groups. Tables were of a different size than in fall semester, but stick units were the same size. N=8.

One item of interest regards error in both the fall and spring groups. Both were asked to an estimate of measurement error (specifically “+/-”) but not instructed how to obtain this value. This issue was a secondary concern in this lab activity, and the question was included to determine whether there was a need for more time and instruction on that concept/skill set. Fall groups mostly gave error ranges that were much smaller than the measurements warranted, with the exception of groups 3 and 6. Group 3 correctly surmised that the smallest fractional remainder was the proper basis for determining the precision of the measurement. (Group 6 did not indicate in their work any particular reason for their range of error being so large.) Spring-semester groups tended to assume that the “+/-” included the maximum and minimum range limits of the three measurements rather than inherent error in the measurement method. In both cohorts these results indicate misunderstanding of measurement error on a fundamental level.

**Task Ability Changes**

Figure 1 indicates the progression of student assessment results in fall and spring semesters. For each portion of the figure, assessment items are shown in time progression along the x-axis (note that the spacing is not “to scale” in terms of the amount of time between assessments; the figure just shows the order in which things happened). Each of the different assessment items were rated for rigor along a relative difficulty scale (y-axis) from low to very high. The low-difficulty item was the pre-lab quiz, which required students to reduce an already-provided terminating continued fraction. The medium-difficulty level included the pre- and post-course test items (identical) which gave a terminated continued fraction and asked for a percentage equivalent. The high-difficulty items were the first exam in
each semester. Each required students to set up a continued fraction from text description, reduce it, and give a decimal equivalent (in the fall, this last item was the graded item, while in the spring semester each section received separate credit). The exam 2 item in the spring semester gave a reduced fraction and required students to work backwards to determine the measurement remainders using continued fractions techniques; the difficulty of this item was rated as very high.

Figure 1. Student Assessment Results. Relative difficulty is selected by the authors to indicate the level of rigor of the question for each assessment. Time in semester shows the progression of assessments, with the fall sequence being 1-pre-course test, 2-pre-lab quiz, 3-exam 1, 4-post-course test. Spring sequence was 1-pre-lab quiz, 2-exam 1, 3-exam 2. Student average scores are shown beside each data point. N=27 in fall and N=8 in spring, with some occasional absences.

Taking the difficulty into account, it becomes possible to compare like kinds of fruit, so to speak. Students in the fall cohort improved by 40 percentage points on the same question between the pre-course and post-course test. Students in the spring semester showed an improvement of 7 percentage points between the pre-lab quiz and the first exam, despite the significant increase in rigor. There were no other activities in that semester utilizing this skill, therefore it seems reasonable to infer that this lab activity was helpful to the spring students. The later drop of 35 percentage points is attributable to the rigor of the question (the thought process of the author being that if 70% of the students can already do the item correctly, an increase in rigor is warranted). However, the improvement from the lab activity shown on the first exam was not noted in the fall – in fact, there was a drop of 37 percentage points from the pre-lab quiz to the first exam during that semester, despite essentially the same activity.
Discussion: Collateral Benefits

This unit sticks–continued fractions exercise is rich with teaching and learning opportunities. One of the benefits of the activity is that the arithmetic can reveal for some advanced students that there are hazards with a seemingly elementary task that they are apt to take for granted because it is taught in the fifth grade. The task is *adding fractions.* The insidiousness of this common deficiency is well known to the quantitative literacy (QL) community (e.g., Tucker 2008; Schield 2008). For example, quoting Tucker (2008, 75):

… It is in the transition from whole number arithmetic to fractions that too many students fall off the ladder of mathematical learning. They continue their education and become adults without ever understanding fractions.

Consider the following question on the TIMSS 8th grade test:

Find the approximate value, to the closest integer, of the sum 19/20 + 23/25.

Possible answers were a) 1, b) 2, c) 42, d) 45. (Answer: b) The majority of U.S. students chose c) or d). These students did not think of a fraction as a number. When asked to add two fractions and get an integer answer, they added the numerators or the denominators of the two fractions. The only numbers that they knew about were counting numbers (whole numbers). A fraction to them was some combination of two whole numbers. To be fair, *fractions are a sophisticated mathematical concept compared to whole numbers* (emphasis added).

Fast forward to our senior-level, geology-major QL course populated with students who, for the most part, have had at least one semester of calculus. Following is the continued-fraction question on the midterm for the fall semester class.

Suppose that you are conducting a measurement, much as you did in Vic’s Lab 4, using an unruled Denis stick (symbol Ж). You measure the width of your computer screen and find that it measures 2 Ж with a remainder. The remainder, when compared to the Denis stick, fits in 2 times, with a second remainder. The second remainder fits into the first remainder 4 times, with a third remainder. The third remainder fits exactly into the second remainder 2 times (no remainder). What is the width of your computer screen? Give your answer to hundredths of a Denis. (Hint: use the method of continued fractions).

The answer is 2.45 Ж, which can be obtained by:

\[
\text{length} = 2 \text{ Ж} + \frac{1}{2+\frac{1}{4+\frac{9}{20}}} \text{ Ж} = 2 \text{ Ж} + \frac{1}{2+\frac{9}{20}} \text{ Ж} = 2 \text{ Ж} + \frac{9}{20} \text{ Ж} = 2.45 \text{ Ж}.
\]

About 40% of the students gave the correct answer. One of the incorrect answers was 2.41 Ж. The result was obtained by

---

8 Coincidentally, another paper in this issue of *Numeracy* deals explicitly with a group of journalism students and their experience with adding fractions. See Harrison, “Journalists, Numeracy and Cultural Capital.”

9 See also Devlin 2005, 230–233).
\[
\text{length} = 2 \mathcal{K} + \frac{1}{2 + \frac{1}{4 + \frac{1}{2 + \frac{1}{\mathcal{K}}}}} = 2 \mathcal{K} + \frac{1}{2 + \frac{1}{4 + \frac{1}{2 + \frac{1}{\mathcal{K}}}}} = 2 \mathcal{K} + \frac{2}{22} \mathcal{K} = 2.41 \mathcal{K},
\]

where the greyed expression shows the incorrect step. The point in the steps internal to that shaded incorrect step were

\[
2 \mathcal{K} + \frac{1}{2 + \frac{1}{4 + \frac{1}{2 + \frac{1}{\mathcal{K}}}}} = 2 \mathcal{K} + \frac{1}{2 + \frac{1}{4 + \frac{1}{2 + \frac{1}{\mathcal{K}}}}} = 2 \mathcal{K} + \frac{2}{22} \mathcal{K} = 2 \mathcal{K} + \frac{1}{\frac{22}{9}} \mathcal{K},
\]

where again the grey shading shows the misstep. The mistake is \(8/2 + 1/2 = 9/4\); in other words, the addition was done by adding the numerators and the denominators.

Surely our senior geology students know that \(4 + 1/2\), which is obviously larger than 4, is not equal to \(9/4\), which is only a little larger than 2, but in the “heat of the moment” one can lapse into bad technique when focusing intently on another part of a calculation, such as, in this case, the steps involving reciprocals of fractions. Thus the calculation itself provides teaching opportunities. An obvious one here is Step 4 of Polya’s *How to Solve It* classic (Polya 1945): Looking back (Check your work!).

The calculation also provides the opportunity for brief, beneficial digressions, which help enliven interactive exchanges available in a comfortable lab environment. For example, there is the concept of mediant

\[
\text{mediant} \left(\frac{a}{b}, \frac{c}{d}\right) = \frac{a+c}{b+d},
\]

and the quotation from Conway and Guy (1996, 153), in connection with Farey fractions (noting *en passant*, and in context appropriate to our class, that John Farey, 1766–1826, was an early geologist\(^{10}\)),

Warning: forming the mediant is not the way to add fractions, unless you’re calculating batting averages!

The Conway and Guy quotation then provides a nice segue to “baseball math.” For example, suppose a batter with 10 hits in 40 at bats (batting average 0.250) has a good day with 4 hits in 4 at bats. What is the batter’s new batting average? The numerical answer is 14/44 = 0.318. However, the students know perfectly well that 10/40 + 4/4 is 1.25. From a QL in Computational Geology perspective—where the concept of units is paramount—the discrepancy is immediately cleared up with units and a reminder of the schema for the weighted arithmetic mean, one of the stalwart and recurring subjects of the course. For

\(^{10}\) James Hutton (see footnote 3) is widely regarded as the “father” of geology with publication of his *Theory of the Earth* in 1788. Thus Farey was roughly the age of our students when geology was born, and the Earth was seen to be unimaginably old.
here, the question is asking for the average of two ratios, 0.250 hits/at bats and 1.000 hits/at bats, weighted by 40 at bats and 4 at bats, respectively. Thus

\[
\frac{(40 \text{ at bats})(0.25 \text{ hits/at bats})+(4 \text{ at bats})(1.00 \text{ hits/at bats})}{(40 \text{ at bats})+(4 \text{ at bats})} = \frac{14 \text{ hits}}{44 \text{ at bats}}
\]

Finally, the mistake in context provides a convenient point on our side for holding firm on no partial credit. While there may be a tendency for some students to think that 2.41 is close enough to 2.45 to warrant some partial credit, those students are easily convinced that size of a numerical difference is not proportional to the magnitude of the error in terms of their own fundamental arithmetic skills. Not even the most recalcitrant, point-counting student would argue that quantitative thought equivalent to \( \frac{1}{2} + \frac{1}{2} \) equals \( \frac{2}{4} \) should be in any way acceptable.

**Concluding Remarks**

The “stick lab,” having been piloted twice in the Computational Geology course at USF, had the learning objectives of helping geology students (a) wake up about pitfalls of adding fractions, and (b) think about terminated continued fractions in a practical way that has a possible (if unlikely) field usage, with a secondary observation objective (c) to determine student understanding of measurement error. Preliminary results indicate success at achievement of learning objectives (a, b) with the need for further study indicated due to relatively small class numbers, and poor understanding of measurement error observed in both classes regarding (c). Class sections beginning in fall 2016 will continue to perform the lab activity, with the spring 2016 modification of taking three sets of measurements for each dimension in place.

It is interesting that students did not show prior learning in scientific measurement techniques, an absence which indicates a need for an adjustment in future semesters. The listed topic of the lab (when given to the students) was “Measurement and Error”. Student responses were not reasonable or consistent with standard scientific practices with regards to measurement error. The backgrounds of the students are generally varied, but as this is an upper-level geology course, it is expected that this activity is by no means the first time students have performed measurements or recorded uncertainty. However, student concepts of error, how to measure error, and how to report measurements containing error indicate a definite need to alter course instruction before this lab is introduced in fall 2016 so that students are familiar with basic scientific expectations and procedures for measurement and assessing measurement error.
Appendix: Student Handout (fall semester 2015)

Lab 4: Measurement and Error

This lab is going to operate a little differently than the previous labs, and probably a bit differently than the labs that came before. This time, you’re going to be presented with a problem in the life context, and I’m not going to tell you how to solve it. Well, not much, anyway.

Materials: You will be given a piece of plastic without any markings in or on it. Please do not do anything to this item! This is part of the slide rule we’re going to use later in class, and there was a lot of time and effort (and a reasonable amount of money) that went into their construction. We have no more of them! So please, don’t mark them, don’t cut them, and don’t leave them where they might melt, like on the seat of a hot car (I learned that one the hard way with our prototype). You may NOT use any rulers or similar measurement devices, or apps that simulate them.

Scenario: You and a small group of coworkers are stranded after a crash. You have nothing with you that can be used for “known” distance measurements, like a meter stick or ruler. What do you do?

The basic answer to this is you take something nearby that is sturdy enough to serve as a basic unit. It could be a stick, or a piece of metal, or a length of PVC, as long as it is easy to tell where it starts and ends, and that doesn’t change. You then measure things in terms of how many of this local unit they are in length (we can call it a “Denis” and give it the unit marker “Ж” (Dr. Denis Voytenko is the former TA of this course, and the Cyrillic character is in his honor). The easy part is measuring that, say, the width of the doorway in front of you is a bit more than 5 Ж. The hard part is, how much more than “a bit”? How do you go from “a bit more than 5” Ж to 5.24 Ж?

One solution is to use continued fractions. You have to mark out (on something other than my ruler piece!) what the remainder is, and then determine how many times that piece divides back into the original ruler. If there’s a remainder left when you measure that out, you have to repeat the procedure!

Assignment: Given only the unmarked ruler, and adding to this only paper and marking equipment (i.e., pencil or pen), measure the width of one of the tables in the classroom (the ones you are all sitting at that are all the same size). For clarity here, assume that the length of the slide rule piece the long way is 1 Ж.

1. Working in groups of 2-4, measure the length and width of your tabletop in continued fractions of a Ж as precisely as you can, and then convert the continued fraction to two decimal points (i.e., 14.54 Ж); then calculate the area of the tabletop surface in Ж². For this exercise, assume the corners of the desk are perfectly square, rather than slightly rounded, so take your measurements slightly off the very edge.

2. Estimate the error of all three measurements (length, width, area). That is, your measurements are +/- how many Ж, Ж², or fractions/decimals thereof?

3. Report your solutions to the above to the class on the board before the end of class so that a distribution of class measurements can be determined.

Items 1 and 2 are due at 10:30, so we have time to complete the rest.
References


A Twenty-Year Look at “Computational Geology,” an Evolving, In-Discipline Course in Quantitative Literacy at the University of South Florida

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A Twenty-Year Look at “Computational Geology,” an Evolving, In-Discipline Course in Quantitative Literacy at the University of South Florida

Abstract
Since 1996, the Geology (GLY) program at the USF has offered “Computational Geology” as part of its commitment to prepare undergraduate majors for the quantitative aspects of their field. The course focuses on geological-mathematical problem solving. Over its twenty years, the course has evolved from a GATC (geometry-algebra-trigonometry-calculus) in-discipline capstone to a quantitative literacy (QL) course taught within a natural science major. With the formation of the new School of Geosciences in 2013, the merging departments re-examined their various curricular programs. An online survey of the Geology Alumni Society found that “express quantitative evidence in support of an argument” was more favorably viewed as a workplace skill (4th out of 69) than algebra (51st), trig (55th) and calculus 1 and 2 (59th and 60th). In that context, we decided to find out from successful alumni, “What did you get out of Computational Geology?”

To that end, the first author carried out a formal, qualitative research study (narrative inquiry protocol), whereby he conducted, recorded, and transcribed semi-structured interviews of ten alumni selected from a list of 20 provided by the second author. In response to “Tell me what you remember from the course,” multiple alumni volunteered nine items: Excel (10 out of 10), Excel modules (8), Polya problem solving (5), “important” (4), unit conversions (4), back-of-the-envelope calculations (4), gender equality (3). In response to “Is there anything from the course that you used professionally or personally since graduating?” multiple alumni volunteered seven items: Excel (9 out of 10), QL/thinking (6), unit conversions (5), statistics (5), Excel modules (3), their notes (2). Outcome analysis from the open-ended comments arising from structured questions led to the identification of alumni takeaways in terms of elements of three values: (1) understanding and knowledge (facts such as conversion factors, and concepts such as proportions and log scales); (2) abilities and skills (communication, Excel, unit conversions); and (3) traits and dispositions (problem solving, confidence, and QL itself). The overriding conclusion of this case study is that QL education can have a place in geoscience education where the so-called context of the QL is interesting because it is in the students’ home major, and that such a course can be tailored to any level of program prerequisites.

Keywords
Quantitative literacy, STEM, geoscience education, Polya heuristic, spreadsheets in education

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Cover Page Footnote
Vic Ricchezza and Len Vacher are a doctoral student/teaching assistant and professor, respectively, in the Geology program in the School of Geosciences at the University of South Florida, Tampa.

This article is available in Numeracy: http://scholarcommons.usf.edu/numeracy/vol10/iss1/art6
Introduction

The path by which Quantitative Literacy\(^1\) became a widely held learning goal for mathematics education in U.S. colleges and universities (e.g., Rhodes 2010) is associated with the names of some pioneer educators in the Mathematics Association of America (MAA) around the turn of the 21st century. Foremost among these individuals are Linda Sons for the massive report of the MAA Subcommittee on Quantitative Literacy Requirements (the “Sons report,” Sons et al. 1997); Lynn Steen for Mathematics and Democracy (Steen 2001), a seminal collection of essays, which made the case for quantitative literacy; and Bernard L. Madison for “Quantitative Literacy: Everybody’s Orphan,” an editorial in an MAA Focus newsletter (Madison 2001). The latter, “Everybody’s Orphan,” sets the frame for this paper, for in it, Madison articulated an issue that is still unresolved. In our opinion, the case example we describe in this paper illustrates a grassroots (as opposed to an administrative top-down) approach that can help address it.

According to “Everybody’s Orphan,” education in numeracy (QL) education was suffering because no one claimed responsibility for it in our discipline-focused curricula of the time. The mathematical content of QL rests on mathematics covered in the mathematics curriculum with the effect that, in practice, QL and mathematical literacy (ML) were considered the same thing by many non-mathematicians. So, of course, QL belonged in the mathematics curriculum; never mind that mathematics departments were already serving the many needs of the many mathematics prerequisites of many client departments. On the other hand, QL is richly “contextual,” while students in mathematics “are asked to rise above context” while they learn mathematics (Madison 2001, 10). Moreover, as simultaneously laid out by Devlin (2000) in his “The Four Faces of Mathematics,” QL is a fundamental life skill in today’s society, on par with literacy. It is the responsibility of every teacher. It sends the wrong message to our students if we regard basic quantitative skills as different from basic language skills. “Confusing quantitative literacy with mathematics simply confounds the problem” (Devlin 2000, 24).

Meanwhile, our discipline—geology, one of the mathematics departments’ smaller client departments—was grappling with mathematics in context, as QL has come to be known, from the context side of the trope. For example, in

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\(^1\) QL, also known as quantitative reasoning [QR] and numeracy; see Vacher (2014), Roohr et al. (2014), Karaali et al. (2016) for semantics. As discussed by Karaali et al. (2016), the semantic swamp also includes distinctions between mathematical literacy [ML] and QL (and QR and numeracy).
September 2000, the *Journal of Geoscience Education* published a special theme issue titled “Building the Quantitative Skills of Students in Geoscience Courses” (Macdonald et al. 2000a, b). Most of the 22 papers in the special issue addressed the strategy of embedding some mathematics into geoscience courses, particularly at the introductory level. Only two of the papers concerned a standalone geology course in which mathematics was the number-one priority. One (Lutz and Srogi 2000), from West Chester University, told of a geology shadow course that students take concurrently with their required calculus course; the course objective was to provide context-based problems for the students to solve in order to reinforce and illuminate the mathematics being taught in the linked mathematics course. The other paper described a senior-level course explicitly devoted to geological-mathematical problem solving. From the abstract (Vacher 2000a, 478):

*Computational Geology* is a spreadsheet-intensive, geological-mathematical problem-solving course recently developed at the University of South Florida. Requested by nontraditional students and now a required part of the geology curriculum, the course finishes off the required calculus sequence and its prerequisites. It makes connections between the various strands of mathematics and between mathematics and geology. It aims to enhance mathematical literacy and computational skills and to improve the mathematical comfort level of our students. It also promotes a mathematical problem-solving disposition that is useful to students regardless of whether they remain in geology.

That Computational Geology course is the subject of the present paper. In essence, as pointed out by one of the reviewers, it is “Part 2 to that *JGE* article some 16 years ago.” In particular, our paper illustrates how the course has evolved from a course in mathematics concepts in geology to a course in QL in geology, as the instructor (the second author, HLV) learned of and came to value QL as a learning goal. The paper features interviews of 10 selected alumni of the course conducted as part of a qualitative research study (Ricchezza 2016) by the teaching assistant of the past two years (VJR). As pointed out by another reviewer, the study does not constitute, nor does it aim to be, an evaluation: the ten interviewees had multiple biases; the course evolved over the time of the sample’s exposure; the number of interviewees is small, and most of them had connections to the course and instructor beyond being a student. Rather, that reviewer continues, the paper provides a case study of a QL course outside the mathematics department, in fact, in a STEM (Science, Technology, Engineering, Math) discipline. The qualitative study, in the words of the first reviewer, provides information “regarding the lived experiences of the participants in it and of the perceived benefits that the course provided” to them. The following narrative, then, starts with background history and evolution of the course, reviews the data of the qualitative study (Ricchezza 2016), and ends with a “So What?”
Background on the Course

Computational Geology (hereafter, CG) was first offered in Spring 1996 under a different name “Math Concepts in Geology.” It was offered once per year, usually in the fall. As of Fall 2015, it is now being offered every semester. Annual enrollments have doubled from 10-20 in the beginning to 30-40 now, in keeping with the growth of the geology program. Beginning in Spring 2016, the spring versions are being taught by a different professor (Chuck Connor, a volcanologist; HLV is a hydrogeologist; QL crosses subdisciplines in geology).

The Early Years

Vacher (2000a, 478) described how the course came to be. The explanation makes it evident why the course aims to be conspicuously useful to the students:

The Tampa campus of the University of South Florida is an urban university in which older, nontraditional students make up a large proportion of the undergraduate cohort. Many of the geology students have come to university after finding that the lack of a college degree was a problem, and they want to be prepared to do well in their jobs after graduation. Several years ago, some of these older students recognized the incongruity of their mathematics comfort level with their expectations about the importance of mathematics. As one of them put it to me: ‘We insist that our kids know their math. I am not comfortable that I know mine well enough to do anything with it.’ She and a small group of other like-minded students persuaded the geology majors to petition for a course that would help them learn to use mathematics in geology. That was the start of *Computational Geology*....

The math-in-context nature of the course is apparent from the 1997 syllabus (Vacher 2000a, 478)

This is a problem-solving course. The purpose is to enhance computational skills and increase *mathematical literacy*... If you are uncomfortable with math or if you find your eyes glazing over when you come to the mathematical parts of your geology textbooks, you need to take this course. Sooner or later you will need to understand quantitative material – or else ignore an increasingly important part of your chosen field. College is the time to do it – not when you are out being paid as a skilled professional by someone who assumes you are *math-literate* and know what you are doing. (*Emphasis added*)

The content of the course listed in the 1997 syllabus is in Table 1. As recounted in Vacher (2000a), for each of the first couple of years, the topics were determined in a conversation with the students during the first class session. Looking at that list of topics now in combination with the use of *mathematical literacy* and *math-literate* in the statement of purpose quoted in the previous excerpt, it is worth noting HLV did not know or appreciate either the term or the concept of *quantitative literacy* at the time. Since then, the content of Computational Geology at USF has co-evolved from an ML-in-geology course to
a QL-in-geology course as its instructor evolved from a STEM-oriented, GATC\textsuperscript{2} path-to-calculus guy to a staunch advocate of QL/QR as inspired in general terms by Steen and Madison (see citation-Numeracy indexes in Vacher 2016 and Grawe and Vacher 2017 respectively) and defined more specifically for the QL needs of students like ours by Gaze (2014).

\begin{table}[h]
\centering
\caption{Content of Original Computational Geology Course. From the 1997 syllabus (Vacher 2000a)}
\begin{tabular}{|c|p{10cm}|}
\hline
Part & Topics \\
\hline
I & Problem solving, computational strategies. Significant figures. Dimensions, unit conversions. \\
II & Functions, especially polynomial functions, \(\exp(x)\), \(\ln(x)\), \(\log(x)\), and \(a^x\). Taylor series. Error propagation. \\
III & Lines, triangles, vectors, simultaneous equations, determinants. \\
V & Descriptive statistics. Concepts of random variable, probability, and probability density function. \\
\hline
\end{tabular}
\end{table}

At the same time that the content of the course co-evolved with the instructor’s thinking of and about QL, the conduct of the course co-evolved with his progressing experience using spreadsheets to teach mathematics in context. At the same time, too, both the number of \textit{JGE} papers that involved geological-mathematical exercises, problems or projects was increasing (see Vacher 2000b for bibliography), and the \textit{JGE} papers involving mathematics were increasingly using spreadsheets (see Fratesi and Vacher 2005 for bibliography).

For the Computational Geology course, the initial use of spreadsheets (circa 1997-1998), again, is described by Vacher (2000a):

\begin{quote}
The course is a lecture course. The lectures are about mathematics. Geology is used to motivate the mathematics. All the mathematics is used to solve problems via multiple spreadsheet exercises each week. Students work on these exercises outside of class, individually or in groups – whatever works for them. They hand in the spreadsheet for a grade and revise it if necessary – repeatedly if necessary – until the output, including intermediate steps, is correct.
\end{quote}

Soon thereafter (circa 1999), those “lectures … about mathematics” gave way to short, “just in time” explanations of mathematics inserted into a framework of spreadsheet problems addressing geological questions (Vacher 2000a, 480). The first such spreadsheet problem in the course was “How Large is a Ton of Rock?” (Fig. 1). For example, as described by Vacher (2005) in the cover page for the subsequently developed module in the SERC\textsuperscript{3} repository:

\begin{quote}
2 Geometry, algebra, trigonometry, and calculus (see Gaze 2014 for nomenclature and discussion of how the GATC approach contrasts with the needs to develop QL and QR in all students).

3 Science Education Resource Center at Carleton College. \url{http://serc.carleton.edu/index.html}
\end{quote}
(This problem) comes in the second week of the semester. It accompanies the first problem-solving session. The preceding session is a computer-lab session which introduces Excel. The *Ton of Rocks* problem-solving session happens in a lecture room equipped with computer and projector. I start the session by posing the question: "How large is a ton of rocks?" I introduce the class to the fact that the class sessions will consist of such questions, and that they will be dividing up into groups to consider how to solve those questions. We discuss strategies of working in groups, and they go after the ton of rocks question.

The students soon decide that they need to know what kind of rock they are thinking about. What kind of minerals are in it? And what do I mean by “how large” anyway? The calmer tables think I mean volume. The more demonstrative tables motion the dimensions (length, width, height) of volumes. So we discuss the first step of Polya's heuristic⁴: understanding the problem and drawing a figure. With agreement as to what the problem is (and a decision to start with a monomineralic rock), they discuss amongst themselves strategies to come up with a calculated length. They successfully design a plan in time for me to show them the first spreadsheet … and discuss it before the end of the 1-1/2 hr session. They leave the session to complete the (assignment), (polymineralic rocks), which has "gone live" on Blackboard during the class session….

… (In the process), students calculate the volume and then edge length of a cube, and the diameter of a sphere, of a variety of rocks weighing a ton. As part of the problem-solving activity, students build a spreadsheet to do the calculation, figuring out the cell equations as they go. The activity focuses on density and examines how this physical property varies with the kind and percentage of the minerals composing the rock. The rocks are: ice; vein quartz; gabbro; granite; porous arkose. The central quantitative issue is the weighted average. Students also need to apply their knowledge of the volume of spheres and cubes, and of course they get practice with unit conversions.⁵

![Image of students working on a computer]

Figure 1. USF Geology students being introduced to their first SSAC module, *How Large is a Ton of Rocks?* Photo by Dorien McGee, Sept 2006. See Teaching with Spreadsheets across the Curriculum, [http://serc.carleton.edu/sp/ssac/index.html](http://serc.carleton.edu/sp/ssac/index.html)

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⁴ Polya 1957

⁵ Note that the central quantitative issue, weighted average, is a key tenet of QL, and certainly so are unit conversions (i.e., proportional reasoning). But, according to some, the use and particularly recall of geometric formulas for volumes would smack of ML. For us (from STEM), geometry (and algebra) in context belongs in QL just as much as arithmetic in context does.
Spreadsheet Modules

The experience with spreadsheet-based assignments such as “How Large is a Ton of Rocks?” led to a sequence of NSF projects that, in aggregate, built a library of spreadsheet modules at SERC. The three projects were “Spreadsheet Exercises in Geological-Mathematical Problem Solving” (2002-2004), “Spreadsheets Across the Curriculum” (2005-2010) (Vacher and Lardner 2010), and “Geology of National Parks: Spreadsheets, Quantitative Literacy, and Natural Resources” (2009-2012) (Vacher et al. 2012).

The Spreadsheets Across the Curriculum (SSAC) library on SERC consists of four collections with nearly a hundred modules:

1. The General Collection: 55 across-the-curriculum modules, mostly from the 2005, 2006, and 2007 module-making workshops of the SSAC project. The modules, which range over 26 Library of Congress categories, were developed by 40 authors from 21 educational institutions in 11 states. Some of the modules from the 2002-2004 project were absorbed into this General Collection for wider dissemination.

2. The Geology of National Parks Collection: 26 modules made in collaboration with eight Research Learning Centers of the National Park Service as part of the 2009-2012 project.

3. The Physical Volcanology Collection: 9 modules developed by Chuck Connor (USF) and Peter LaFemina (Penn State) for their respective courses (2007).

4. The Geologic Hazards Collection: 9 modules developed by Tom Juster (USF) for his courses (2010-2011).

Each of the collections are cataloged with links enabling the collection to be searched by QL topic (Table 2).

As the SSAC library of spreadsheet modules was developed, they became a central focus of the Computational Geology course (McGee 2010). Table 3 lists the 14 modules used in the 2007 version of the course (25% of grade). Their use is described in the following from the 2007 syllabus:

Much of the course will involve PowerPoint modules that elaborate on one or more geological-mathematical problems and how to solve them with spreadsheets. You will be asked to modify these spreadsheets in some way and hand in something to be graded. You will need to recreate the spreadsheets, including the cell equations. This work will take quite a bit of thought in some cases. You may work together on these assignments, but do note that the quizzes/exam will assume that you have the skills required to do the spreadsheets.

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6 http://nsf.gov/awardsearch/showAward?AWD_ID=0126500&HistoricalAwards=false
7 http://nsf.gov/awardsearch/showAward?AWD_ID=0442629&HistoricalAwards=false
8 http://nsf.gov/awardsearch/showAward?AWD_ID=0442629&HistoricalAwards=false
<table>
<thead>
<tr>
<th>Breakdown</th>
<th>Collection*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Quantitative Concepts</strong></td>
<td>GC</td>
</tr>
<tr>
<td>Basic arithmetic; number sense</td>
<td>51</td>
</tr>
<tr>
<td>Measurement; Data presentation and analysis; Probability</td>
<td>45</td>
</tr>
<tr>
<td>Algebra; Modeling; Functions</td>
<td>37</td>
</tr>
<tr>
<td>Geometry; Trigonometry</td>
<td>11</td>
</tr>
<tr>
<td>Calculus; Numerical methods</td>
<td>11</td>
</tr>
<tr>
<td>Creating and manipulating tabular data</td>
<td>40</td>
</tr>
<tr>
<td><strong>Excel Skills</strong></td>
<td></td>
</tr>
<tr>
<td>Basic arithmetic</td>
<td>51</td>
</tr>
<tr>
<td>Angles and trig functions</td>
<td>5</td>
</tr>
<tr>
<td>Other elementary math functions</td>
<td>5</td>
</tr>
<tr>
<td>Statistical functions</td>
<td>7</td>
</tr>
<tr>
<td>Logic functions</td>
<td>6</td>
</tr>
<tr>
<td>Graphs and charts</td>
<td>35</td>
</tr>
<tr>
<td>Other manipulations and functions</td>
<td>10</td>
</tr>
<tr>
<td><strong>Subjects (Context)</strong></td>
<td></td>
</tr>
<tr>
<td>Mathematics, statistics and computers</td>
<td>20</td>
</tr>
<tr>
<td>Natural science</td>
<td>28</td>
</tr>
<tr>
<td>Social science</td>
<td>6</td>
</tr>
<tr>
<td>Library and information science</td>
<td>1</td>
</tr>
<tr>
<td>Humanities</td>
<td>2</td>
</tr>
<tr>
<td>Business, economics and finance</td>
<td>10</td>
</tr>
<tr>
<td>Engineering, agriculture</td>
<td>2</td>
</tr>
<tr>
<td>Education</td>
<td>3</td>
</tr>
<tr>
<td>Health</td>
<td>5</td>
</tr>
</tbody>
</table>

*Abbreviations: GC, General Collection; GNP, Geology of National Parks Collection; PV, Physical Volcanology Collection; GH, Geologic Hazards Collection

That year (2007) was one of the handful in the 2000’s that spreadsheet modules were so infused into the thinking of the course that the students made and presented a module as a team project (25% of grade). From the syllabus:

By mid-October you will have seen and worked through several Spreadsheet Modules. The Team Project is for you to develop, present, and post one of your own. Teams will consist of ~3 students. Each team will develop and present a Spreadsheet Module. Every member of the team must participate in the presentation. There will be a team grade based on the quality of the module, the presentation, every team member’s understanding of the geological-mathematical problem(s) and solution(s), and the professionalism of the presentation and presenters. “Quality of the module” includes the content level of the geological-mathematical problem, the correctness of the solution, and the effectiveness of the module. “Effectiveness” will be judged by the following question: Would students benefit from working through the module? Individual grades will be the team grade times a weighting factor worked out from a matrix of teammate-generated distribution functions.
Table 3.
Spreadsheet Modules Used in Computational Geology, 2007

<table>
<thead>
<tr>
<th>Module</th>
<th>Authors, institutions*</th>
<th>Quantitative Skill**</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 How large is a ton of rock? – Thinking about rock density</td>
<td>Len Vacher (2005a), USF</td>
<td>Weighted average. Also, unit conversions, ratio, rearranging equations, volume, trial and error strategy to solve inverse problem</td>
</tr>
<tr>
<td>2 Is it hot in here? – Spreadsheeting conversions in the English and metric systems</td>
<td>Cheryl Coolidge (2006), Colby-Sawyer College</td>
<td>Unit conversions. Also, scientific notation, ratios, orders of magnitude; rearranging equations; XY scatter plot, trend line; linear function</td>
</tr>
<tr>
<td>3 Earthquake magnitude: How can we compare the sizes of earthquakes?</td>
<td>Laura Wetzel (2005), Eckerd College</td>
<td>Order of magnitude and logarithmic scales. Also, scientific notation, ratios, rearranging equations, linear and semilogarithmic graphs</td>
</tr>
<tr>
<td>4 Calibrating a pipettor</td>
<td>Bill Thomas (2005), Colby-Sawyer College</td>
<td>Variability and precision vs. accuracy. Also, mean and standard deviation; relative and percent error; bar and scatter graphs</td>
</tr>
<tr>
<td>5 Frequency of large earthquakes – Introducing some elementary statistical descriptors</td>
<td>Len Vacher (2006a), USF</td>
<td>Exploratory statistical descriptors. Also, mean, median, mode; variance, standard deviation; percentiles, quartiles; interpolation; normal distribution</td>
</tr>
<tr>
<td>6 Shaking ground – Linking earthquake magnitude and intensity</td>
<td>Eric M. D. Baer (2006), Highline Community College</td>
<td>Forward modeling. Also, logarithmic scales, unit conversions, Roman numerals, exponential and power functions, reading graphs, map scale</td>
</tr>
<tr>
<td>7 How large is the Great Pyramid of Giza? – Would it make a wall that would enclose France?</td>
<td>Len Vacher (2006b), USF</td>
<td>Estimation. Also, unit conversions, significant figures, volume of a pyramid, ratio of volume to cross-sectional area</td>
</tr>
<tr>
<td>8 From isotopes to paleotemperature: Working with a temperature equation</td>
<td>Dorien McGee (2006), USF</td>
<td>Data analysis. Also, ratios, manipulating equation, correlation, coefficient of determination, line and column graphs, XY-scatter plot</td>
</tr>
<tr>
<td>9 Radioactive decay and popping popcorn – Understanding the rate law</td>
<td>Christina Stringer (2005), USF</td>
<td>Exponential function. Also, geometric progression, dimensions vs. units, rate of change, logarithmic scale, trend line, Law of Large Numbers.</td>
</tr>
<tr>
<td>10 Carbon sequestration in campus trees</td>
<td>Robert Cole (2006), The Evergreen State College</td>
<td>Power function. Also, order of magnitude and scientific notation; allometry; exponential and logarithmic expressions; percentage increase</td>
</tr>
<tr>
<td>11 Buffer capacity in chemical equilibrium: How long can you hyperventilate before severe alkalosis sets in?</td>
<td>Armando Herbelin (2007), Lower Columbia College</td>
<td>Manipulating logarithmic equations. Also, simultaneous equations, what-if modeling, dimensional analysis, scientific notation, slope of trend lines.</td>
</tr>
<tr>
<td>12 How far is yonder mountain? – A trig problem</td>
<td>Len Vacher (2005b), USF</td>
<td>Trigonometry, tangent. Also, effect of measurement error; combining and rearranging equations; finding solution by trial and error; circles and radians</td>
</tr>
<tr>
<td>13 Earth’s planetary density – Constraining what we think of the Earth’s interior</td>
<td>Len Vacher (2006c), USF</td>
<td>Weighted average. Also, unit conversions, volume of spherical shell, inverse problem by trial and error, concept of integral</td>
</tr>
</tbody>
</table>

* See References, Part B. ** Core and supportive quantitative concepts and skills identified by the author(s) on the first page of the published modules.

In addition to the spreadsheet modules, the class consisted of twice weekly lectures, an MAA textbook on QL (Anderson and Swanson 2005) for self-study, pre-lecture warm-up quizzes, and a comprehensive final. One week was open to
allow for in-class team meetings, and two weeks were devoted to presentations and discussions of the team modules. Each team module was tapped for at least one question on the final exam.

**Currently**

The Fall 2016 edition of Computational Geology consists of Tuesday classroom and Thursday lab sessions. The focus of the course overall is interacting with word problems (inspired by reading Sweller et al. 2011). The Tuesday sessions are devoted specifically to ten problem sets consisting of more than 300 exam-type problems developed over the years (Table 4). A problem set is made available on Tuesday for a week of try-on-your-own self- or group-study, and discussed, along with a worked-examples version the next Tuesday, following a warm-up, low-risk quiz (to encourage attendance and the week-long study).

### Table 4.

<table>
<thead>
<tr>
<th>Lecture/Problem Set</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Introductory remarks Pre-test. QL vs. QR vs. Numeracy (vs GATC). Polya and problem solving. Ten principles of QL according to Vacher</td>
</tr>
<tr>
<td>2</td>
<td>PS 1. Numbers and Counting Concepts of arithmetic; traps of fractions; advanced counting (Venn diagrams, inclusion-exclusion); binomial theorem and combinations $Q = n! / r! / (n-r)!$; simple unit conversions; unit conversions with multiple dimensions; non-proportional unit conversions; reciprocal units. Meaning of proportional; meaning of proportion; meaning of percentage; percent of what (Venn diagrams); percent of what (two-way tables); percent of what (percent larger than); percent by what Notation and arithmetic; weighted and unweighted means; averages of ratio quantities (arithmetic mean vs. harmonic mean); geometric means; the integral as a sum</td>
</tr>
<tr>
<td>3</td>
<td>PS 2. Quantities and Units</td>
</tr>
<tr>
<td>4</td>
<td>PS 3. Proportion and Percentages</td>
</tr>
<tr>
<td>5</td>
<td>PS 4. Sums and Averages</td>
</tr>
<tr>
<td>6</td>
<td>PS 5. Ratios and Rates</td>
</tr>
<tr>
<td>7</td>
<td>PS 6. Estimation and Error</td>
</tr>
<tr>
<td>8</td>
<td>PS 7. Circles and Angles</td>
</tr>
<tr>
<td>9</td>
<td>PS 8. Logs and Log Scales Manipulating exponents and logs; phi sizes and Richter Magnitude; exponential decay; log scales; straight lines on graphs with log scales The sloping line; intersecting lines; the inclined plane; three point problem</td>
</tr>
<tr>
<td>10</td>
<td>PS 9. Lines and Planes</td>
</tr>
<tr>
<td>11</td>
<td>PS 10. Modeling Functions</td>
</tr>
<tr>
<td>12</td>
<td>Wrap Up Post-test. What numbers do you remember? What quantities do you remember?</td>
</tr>
</tbody>
</table>

The Thursday sessions consist of six hands-on labs (e.g., Ricchezza and Vacher 2015, Vacher et al. 2016; see Fig. 2) and ten spreadsheet modules, nine of which are from the SSAC Geology of National Parks Collection (Table 5). Three
of the modules are done in the computer lab,\footnote{One of them was actually homework in 2016 because of shutdown due to Hurricane Hermine.} following self-study of two tutorial modules in the SSAC collection. The other six are done as homework assignments, which allow our course to co-exist with the many out-of-state field trips of concurrent discipline-focused geology courses.

The lectures (problem sets) and labs are coordinated. The labs are 30\% of the grade; the lecture material, which is assessed by three exams (the quizzes are a trace constituent), is 50\% of the grade.

The remaining 20\% of the grade involves writing assignments of two types. In the first assignment (10\% of grade), the students submit a total of four word problems (at 2-3 week intervals) to the course management system’s discussion board for substantive (as opposed to frivolous “nice problem”) peer-discussion with an eye toward their potential use in future exams or problem sets. The purpose of this assignment is to have the students experience how difficult it is to write realistic and doable word problems that won’t be misunderstood by somebody (i.e., QL, communication about quantitative material).

For the second assignment (10\% of the grade), students read The Math Instinct (Devlin 2005) and submit a series of private statements on the course management system. In the first week of class, they submit a statement “describing what you think of your experience with mathematics and your attitude toward the subject.” Starting the second week of the semester, they submit a one-paragraph reaction to the successive chapters (there are 13) in the book each week. At the end of the term, they submit a two-page summary report of what they got out of the reading assignment. The purpose of this assignment is to have students experience a good read about math in a context that they likely would not have had thought about before. It also introduces them to another core component of QL, namely disposition and attitude.
### Table 5
### Lab Sessions for Computational Geology, 2016

<table>
<thead>
<tr>
<th>Hands-on Labs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Arithmetic and mental math</td>
<td>Practice on arithmetic calculation without calculators, and on calculations without pencil and paper. Prepare students to look back quickly on problem solutions for quantitative plausibility (Polya heuristic, Part 4).</td>
</tr>
<tr>
<td>2. Unit sticks on an ocean island</td>
<td>Given only a single disposable chopstick use the stick as a basic unit of distance and measure areas of nearby objects to at least 3 significant figures using continued fractions (see Ricchezza and Vacher 2016).</td>
</tr>
<tr>
<td>3. Mt. Everest vs. Mt Kilimanjaro</td>
<td>Students estimate the difference between the length of the Earth’s radius to the tops of Mounts Everest and Kilimanjaro, based on their altitudes. They are then led through a multi-step estimation process to answer the same question considering the Earth’s oblate figure (see Vacher et al. 2016).</td>
</tr>
<tr>
<td>4. Slide rules and log scales</td>
<td>Students use 3D printed logarithmic slide rules to perform a variety of basic arithmetic, logarithmic, and trigonometric calculations. They then construct their own logarithmic slide rule to multiply and divide.</td>
</tr>
<tr>
<td>5. Triangles in the wild</td>
<td>Using clinometers in Brunton compasses, students measure angles to stationary objects on campus, using trigonometry to calculate distances that cannot be directly measured due to inaccessibility.</td>
</tr>
<tr>
<td>6. Graph paper and straight line plots</td>
<td>Students are provided with listed ordered (x,y) pairs to plot on arithmetic, semi-log (log-x), semi-log (log-y), and log-log graph paper, to derive the modeling functions that gives an apparent straight line for list.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Spreadsheet Modules</th>
<th>Authors, institutions*</th>
<th>Quantitative Skill**</th>
</tr>
</thead>
<tbody>
<tr>
<td>0. Spread sheet warm up for SSAC Geology of National Parks modules</td>
<td>Dorien McGee, Meghan Lindsey and Len Vacher, USF (2009)</td>
<td>Concept of function. Also, order of operations, order of magnitude, unit conversions, proportion</td>
</tr>
<tr>
<td>0. Spread sheet warm up for SSAC Geology of National Parks modules, 2: Elementary manipulations ad graphing tasks</td>
<td>Dorien McGee, Meghan Lindsey, and Len Vacher, USF (2011)</td>
<td>Visualization of data. Also, sorting tabular data; bar, pie and line graphs; XY-scatter plots</td>
</tr>
<tr>
<td>1. A percentage stroll through Norris Geyser Basin, Yellowstone National Park</td>
<td>Tom Juster, USF (2010)</td>
<td>Percentage. Also, unit conversions, logarithms</td>
</tr>
<tr>
<td>2. How large is a ton of rocks?</td>
<td>Tom Juster, USF (2011)</td>
<td>Probability and frequency. Also, working with real data, histograms</td>
</tr>
<tr>
<td>4. How much water is in Crater Lake? Using prisms to calculate volume</td>
<td>Mark C. Rains and Len Vacher, USF, and Marian Norris, National Park Service (2011)</td>
<td>Average, mean, median, mode. Also, making and reading graphs; thresholds</td>
</tr>
<tr>
<td>5. Nitrate Levels in the Rock Creek Park Watershed, Washington DC, 1: Measures of central tendency</td>
<td>Len Vacher and Mark Rains, USF, and Marian Norris, National Park Service (2011)</td>
<td>Variance, standard deviation. Also, normal frequency distribution, outlier, percent difference</td>
</tr>
<tr>
<td>7. Dunes, boxcars, and Ball jars: Mining the Great Lakes Shores</td>
<td>Len Vacher, USF; Jim Renfro and Susan Sachs, Great Smoky Mountains NP (2011)</td>
<td>Algorithm. Also, scientific notation, logarithm, unit conversions</td>
</tr>
<tr>
<td>8. Deciviews from Look Rock, Great Smoky Mountains National Park: How hazy is it?</td>
<td>Len Vacher, USF; Susan Sachs, Great Smoky Mountains NP (2011)</td>
<td>Ratio and proportion. Also, scientific notation, unit conversions, graph reading, orders of magnitude</td>
</tr>
<tr>
<td>9. Take a deep breath on the Appalachian Trail in Great Smoky Mountains National Park: How many ozone molecules do you inhale</td>
<td>Tom Juster, USF; Susan Sachs, Great Smoky Mountains NP (2011)</td>
<td></td>
</tr>
</tbody>
</table>

* See References, Part B. ** Core and supportive quantitative concepts and skills identified by the author(s) on the first page of the published modules.
Clearly from Tables 1-5, over the 20 years that the Computational Geology course has evolved, it has been transformed from a GATC bias to a QL course for groups of young scientists who will need to be able to solve challenging and consequential word problems involving quantitative material in their subsequent education and professional lives. This fact is emphasized in the first lecture (Introductory remarks), where the concept of a QL triad is discussed (Fig. 3), and students are given ten QL principles that will appear from time to time during the semester in commentary about the worked examples and during the lab sessions (Table 6).

Table 6
Ten Principles of Quantitative Literacy as Discussion Points in Computational Geology, 2016*

<table>
<thead>
<tr>
<th>Principle</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sets enable logic and are the basis of communication.</td>
</tr>
<tr>
<td>2</td>
<td>Quantities are more than numbers; they include units.</td>
</tr>
<tr>
<td>3</td>
<td>Counting can be difficult, and measurement introduces uncertainties.</td>
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<tr>
<td>4</td>
<td>Uncertainties propagate through calculation.</td>
</tr>
<tr>
<td>5</td>
<td>Ratios (including rates) make comparisons.</td>
</tr>
<tr>
<td>6</td>
<td>Exponents speak magnitude.</td>
</tr>
<tr>
<td>7</td>
<td>Words underperform our thoughts.</td>
</tr>
<tr>
<td>8</td>
<td>Statistics are socially constructed.</td>
</tr>
<tr>
<td>9</td>
<td>Statistics reduce data; averages hide information.</td>
</tr>
<tr>
<td>10</td>
<td>Models (metaphors) are conditional propositions.</td>
</tr>
</tbody>
</table>

* Vacher (2016, unpub.)

Alumni Interviews

Motivation

The Department of Geology merged with programs from the Departments of Geography, Environmental Science and Policy, and Planning to form a new School of Geosciences in Fall 2013. The merger generated the need to rethink all the undergraduate and graduate programs of the former administrative units. The
largest changes occurred in the undergraduate geology (GLY) program, and, notably for this paper, some of those changes affected the “quantitative requirement” and Computational Geology specifically.

Before the revision, calculus 1 and 2 were required for both the BS and BA GLY degrees; there was no statistics requirement; and the BS students were required to take at least two “quantitative geology” courses from a list of four, one of which was Computational Geology (GLY 4866). With the 2016/2017 catalog, a course in elementary statistics has been added to both the BS and BA; calculus 1 is required for both degrees; the calculus 2 requirement for the BS was changed to calculus 2 or Computational Geology (to be renumbered to GLY 3866 in Spring 2017); and, for the BS, students can opt in for a named, transcript-recognized geophysics concentration, which requires both calculus 2 and calculus 3.

To help define the “quantitative requirement” the GLY program’s Undergraduate Curriculum Committee called upon the active alumni network (Rodriguez et al. 2002; Nocita et al. 2016) for input in the form of an online survey. The Likert-type survey listed 69 items under “How important are these skills and resources for geology students entering the workplace?” Averaging of the 23 responses produced the following ranking (emphasis added here):

1. Make oral presentations, …
2. Expository writing.
3. Basic field mapping skills,…
4. Express quantitative evidence in support of an argument…. 
5. Interpret potentiometric surface and water-table maps.
6. Use GPS and/or GIS and/or Remote Sensing instruments, …
7. Utilize existing databases.
8. Explain information presented in mathematical models…
73. Interpret geologic history using existing data…
50. Physics (described).
51. Use algebra and equations to make a geologic calculation.
52. Biostratigraphy …
55. Use trigonometry to solve problems….
69. Engineering calculus 1 (described).
60. Engineering calculus 2 (described).
61. Determine probable genesis and sequence of rock and mineral assemblages.
68. Cellular processes, Biology 1

10 The other three were Hydrogeology; Seismology; Physical Volcanology. Before the two-from-four quantitative course requirement, Computational Geology was required of all majors (BS and BA) from 2000/2001 through 2009/2010. Before 2000, Computational Geology was not listed in the undergraduate catalog.
Determine optical properties of rocks and minerals.

Although the feedback from the alumni had been sought to find out about the whole gamut of geology and supporting courses, and not the quantitative requirement in particular, faculty members interested in “quantitative geology” were especially intrigued by the response relative to the mathematics supporting courses. The discussions prompted questions including “What are students taking away from Computational Geology?” More precisely, “If the students are learning anything in that course, what is it?” In other words, the kind of questions that were being asked was the kind that frequently in our program is met with “Let’s talk to our alumni network.” The timing was good for such conversations, too, because the course had been taught by the same individual since its inception, and for a variety of reasons, there was the potential for change in that regard. So, the time had come to ask, what has been learned from the Computational Geology experience, and what changes might be desirable? Further, because no one in our School of Geosciences is aware of any other geology course in the U.S. like Computational Geology in aiming explicitly at teaching quantitative literacy and geological-mathematical problem solving to geology majors, it was thought that diving more deeply into conversations with the alumni about the takeaways from the course would be of interest more broadly to both the QL community and the geoscience education community. In that context, we decided to investigate the matter by means of a qualitative study (Ricchezza 2016), as the first step along a DBER pathway to a broader investigation of teaching quantitative literacy within geoscience education.

Why start with a qualitative study? Quoting Feig (2011, 2), “Quantitative inquiry can tell a researcher what and how much of something happens, but the question of why is problematic.” We were interested in what the alumni had to say.

**Methodology**

The interview protocol followed a narrative inquiry framework, which means it was intended to elicit the stories of the interviewees (Patton 2015). Questions were selected to be as open-ended as possible and still relate to the overall topic (the CG course and its impacts) in order to see what unexpected things would be said by those with different life experiences. As noted by Clandinin (2006, 44),

Narrative inquiry is an old practice that may feel new for a variety of reasons. It is a commonplace to note that human beings both live and tell stories about their living. These lived and told stores and talk about those stories are ways we create meaning in our lives as well as ways we enlist each other’s help in building our lives and communities.

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11 Discipline-based education research. See http://serc.carleton.edu/NAGTWorkshops/DBER.html
What does feel new is the emergence of narrative methodologies in social science research.

The following practical research questions drove the study:

1. What were the interviewed alumni’s experiences in the course and what memories did they retain?
2. In what ways was the course of practical use to the interviewed alumni in their professional or personal lives, post-graduation?
3. What are the needs of the workforce, as expressed by the interviewed alumni, in regard to what could or should be taught in this course?

Selection of interviewees. Based on the three guiding research questions, HLV made a list of 20 alumni from which VJR recruited ten interviewees. Those persons all met the following criteria:

- Took and passed Computational Geology or Math Concepts as undergraduates between 1997 and 2013.
- Graduated from USF with a BS in geology.
- Were known by HLV to have gone on to professional success within their chosen career field.
- Collectively covered a spread of private sector/consulting, public sector/regulatory, and academic job roles in approximately equal measure.

Regarding the “professionally successful” criterion, it was not a rigorous or measured criterion in any way. Alumni who were deemed to meet this criterion simply met HLV’s personal ideas for professional success as a “yes/no” proposition, and once that was determined, the matter was not considered further. Academics were not judged by whether they had achieved tenure, for example, or consultants were not judged by number or level of clients, or hourly billing rate, and regulators were not judged by caseload, administrative level, or other such criteria. Furthermore, any such consideration would vary according to time since graduation; someone who graduated in 1997 would be presumed to have accomplished a great deal more, professionally, than someone who graduated in 2013. Exclusion of any particular alumni was not intentional and was not a reflection of the ability or success of anyone excluded.

Additionally, the spread of career choices was not universal or random, nor did it cover all possible jobs within the three chosen “branches” of geological careers. As with the criterion of professional success, the inclusion of these interviewees as being sufficiently representative of the public/private/academic work sectors for geologists was not entirely rigorous, but was done for the purpose of seeing whether we could get some variation across the career branches of these accessible alumni.
Interviewees. In accordance with the USF Institutional Review Board (IRB) approval (e22615), interviews with the ten study participants were conducted with informed consent. Participants were granted anonymity through the use of pseudonyms in the interview process, and, to avoid unnecessary bias, interviewees selected their own pseudonyms at the time of the interviews. Informed consent forms, complete transcripts, IRB approval information, and demographic information sheets are all on file with the interviewer.

Luke, Gilda, and Sam are currently employed as regulators at a regional governmental agency. Luke has completed an MS degree, and Gilda and Sam are in the process of doing the same.

John Doe, John Smith, and Medusa work as environmental consultants in the private sector for three different companies. John Doe and John Smith completed MS degrees. Medusa completed an MS degree and holds a state-level professional geologist license. Medusa also has past experience working as a regulator, and teaches introductory college courses part-time, and thus, although categorized by her primary occupation, could be considered under any of the career categories in this study.

Arya and Sunshine earned MS degrees and are currently completing PhD degrees while teaching. Jam earned an MS degree and is a permanent instructor at the collegiate level. Lee is working toward both her MS and PhD degrees.

Jam served as graduate teaching assistant (TA) for the CG course in graduate school. Arya unofficially served in this capacity as well, and wrote and organized a significant portion of the module and module accessory files. Sunshine was employed by HLV (mentioned in her interview) during summers of her MS studies organizing and improving the uniformity of the physical appearance of the modules and spreadsheets.

It should be noted that all but two of the interviewees (Medusa and Lee) did graduate work at USF.

Interviews. The study participants sat with VJR for a semi-structured interview. A semi-structured interview is one where a series of set questions is asked, and follow-up questions are allowed, based on the responses to the original questions. The interview protocol required that the following three questions be asked:

1. Please think back to when you took the computational geology course as an undergraduate at USF. Please tell me what you remember from that course.
2. What, from that course, have you used professionally or personally since graduating?
3. What would you like to see students in computational geology learning that would help them succeed professionally after graduation?

Follow-up questions were permitted and essentially open-ended, and they constituted the bulk of the interview time. Interviews were audio recorded, and participants filled out a demographic information sheet after recordings were
completed. After interview recordings were transcribed and checked for errors, the audio recordings were erased, as voices are identifiable. Transcripts are available on request, but the interviewer reserves the right to redact identifying information before release.

Interviewees were not compensated for participation. Eight of the ten interviews were conducted in person. One participant was located out of state, and another had a work schedule that did not allow time to come to the USF campus. Both of these interviews were conducted via Skype video conference with audio-only recording. Interviewees who conducted their interviews via Skype sent signed copies of their consent forms via email and then orally answered the demographic questions, and the questionnaire was completed by VJR using the answers provided by the interviewees.

Participants were not provided information about the protocol before the interviews other than the name of the study (“Alumni Narratives on Computational Geology”) and an informed consent form indicating that an interview would take place. There were advantages and disadvantages to having interviewees enter the room without having seen the interview questions. On the positive side, interviewees could not rehearse answers. The responses they gave were presumed to represent their own responses and views, without time to change their minds or call a friend for assistance. On the other hand, lack of ability to prepare kept some interviewees (generally those who declared themselves to have poor memory) from having lengthy responses to questions, or remembering specific details. More than one respondent stated some variant of wishing they had a copy of their syllabus in front of them or that they knew what questions were coming beforehand.

The average of all interviews by length of recording was 36.7 minutes. The mean for the three regulators was 23.7 minutes, for the three consultants 33.9 minutes, and for the four academics 48.6 minutes. However, this simple mean reduces the data beyond any useful comparison. The range of time lengths for the interviews ran from 19:53 (Gilda) to 56:51 (Jam). Regulators ranged from 19:53 (Gilda) to 31:06 (Luke). Consultants ranged from 25:17 (John Doe) to 39:40 (Medusa). Academics ranged from 43:40 (Lee) to 56:51 (Jam). Academics did not overlap with either of the other groups’ time ranges, and the overlap between consultants and regulators was small.

**Transcripts.** The interview transcripts were compared with each other for common words, phrases, and concepts using the constant comparative method (Glaser 1965). This method involves physically coding the responses where applicable, that is, highlighting words and phrases that show relevant data and then grouping similar responses where applicable to show trends in the data. This method also analyzes as the data are processed, and compares the various interview transcripts to each other throughout the process. The constant
comparative method has become central to what is known as grounded theory analysis (Strauss and Corbin 1994) where codes are based on the data rather than pre-selected ideas from the interviewers or analysts chosen before analysis. The method of analysis is done in real time, as opposed to prior methods where judgment is suspended until all coding was complete. In reality, some combination of the two is the norm. One cannot sit in an interview room with a participant and hear them speak, listen to the interview recording, transcribe the interview word-for-word, correct the transcript for errors, and then code the transcript without having (at least informally) come to some degree of judgment about the meaning of the codes. Contrariwise, the viewing of fully coded transcripts as a whole gives some insights not apparent on the face of things during the initial stages of the interview and transcription processes.

**Results**

Ricchezza (2016) broke down each interview according to four topic areas: course evolution, course memories, uses of the course post-graduation, and suggestions for the course. Each of the latter three topic areas were further broken down into common suggestions (items mentioned by two or more interviewees) and unique statements (items either said by only one person, or stated in such a unique fashion as to be almost unrelated to the accounts of the other interviewees.)

Of particular interest to QL readers would be life skills and habits of mind—what “serves many functions, including home, school, recreation, finance, work, testing, parenting, and citizenship” (Steen 1997)—and the evolution of the course itself. For the purposes of this article, therefore, we concentrate here largely on the instructional purposes and evolutionary changes through the life of the course and the uses that alumni made of what they learned in their professional and personal lives. To this end, course evolution, selected memories of the course, and later uses of the course are included. The findings in Ricchezza (2016) about suggestions for the course are not included.

**Course evolution (1997-2014).** Although it was not one of the research questions to explore how the mechanics of the course had changed over the years, discussions involving memories about a course would include the mechanics. Numerous points in that regard paint a picture of continual change. Following is an aggregation of memories of the mechanics in chronological order, closing with some memories from VJR when he observed the course in 2014 before becoming the graduate-student Teaching Assistant for it in 2015 and 2016.

Medusa (Spring 1997) described a course without a pre-set schedule of topics,

…he walked in and said ‘what’s holding you up? What sort of concepts are you having trouble with? What’s not working for you? Why are you failing calculus?’ And we spent the first couple of classes talking about that – what we felt we did and didn’t understand,
you know… things for which we didn’t understand the relevance of why they were being presented to us. And he came up with a course description based on that. 12

She described a course where spreadsheets—then not common in other departmental courses—were used to solve problems. The course involved a relatively large amount of calculus, as students had a lot of trouble with this subject in other courses.

Jam (Fall 2001) is the only student to describe the use of a textbook, *Computational Engineering Geology* (Derrinagh 1998), and she also described the use of Excel for problem solving. Homework for the course would consist of both Excel sheets and problems from the text. Class would start with a quiz, which was a homework problem with new numbers. After the quiz, a question or problem would be posed, and group discussion would ensue, which she found frustrating as she didn’t know where to begin. Exams were on paper, but at times required students to explain what they would write in Excel to solve a problem, which Jam also found very frustrating without Excel in front of her to see. She started graduate school the next summer, and spent the summer helping HLV write what would become the first of the PowerPoint modules to accompany the spreadsheets and make them more accessible (see Vacher and Lardner 2005) before serving as TA for the course in 2002.

Sunshine (Fall 2006) described group discussion and paper-based tests. Modules were used as class assignments, as in all later iterations of the course. Sunshine later organized and improved the modules as a graduate student and wrote a new one. There was no textbook for the course, but a series of handouts, namely the “Computational Geology” series of 31 columns published in the *Journal of Geoscience Education* between 1998 and 2005 (Vacher 2005). Selected columns are still used in the course. 13

Gilda (Fall 2008) described there being no TA for the course. She recalled modules and paper exams. Classes began with quizzes that introduced new material, but, “you don’t really ever pass them,” indicating a change from the homework review noted by Jam to more of a background assessment and challenge of misconceptions also observed by VJR in 2014.

Luke (Fall 2009) described module assignments and Excel-based exams. Arya (Fall 2009) also mentioned that the exams were done in Excel. She experienced a lecture-heavy format with the instructor one day per week and an Excel lab session with the TA on the other. She became an unofficial (voluntary undergraduate) TA for the course (Fall 2010), assisting the same TA she had

12 This quote is left “unretouched” to show much of the style of transcription, complete with vocal tics and pauses. All further interview quotes have been “cleaned up” to facilitate easier reading.

13 For the complete list of the Computational Geology columns with full text as published in the *Journal of Geoscience Education* between 1998 and 2005, see

http://www.nagt.org/nagt/jge/columns/compgeo.html
learned from the previous year. She noted that during that semester that the lecture sessions were different in format, with group discussions on solving a common problem. This format was more like what Jam experienced 10 years earlier. Arya noted that there was a campus-wide concern over a potential outbreak of H1N1 swine flu, leading to flexible attendance policies that semester. Lectures were therefore videotaped and posted, which was done only that semester.

John Smith (Fall 2011) described a tough “brain buster” question to start the class, which is consistent with Arya’s account (2010). Exams were in Excel, but may have included portions on paper. Modules were heavily featured, and homework assignments were also in Excel. Sam (also Fall 2011) described Excel-based exams and module-based assignments, and the same class breakup of lecture once per week and a computer/Excel lab once per week with the TA.

John Doe (Fall 2012) said lecture days were generally occupied with a topic lecture the first half and a discussion the second half. Students were given a problem to solve for homework. Exams were mixed method (Excel and paper). Classes began with small quizzes to review material.

Lee (Fall 2013) was in the first class that was asked to write word problems from scratch, rather than simply solve them. Her assignments were module-driven, and she did not mention the format of the exams. However, she correlated exams and Excel by saying, “I didn’t really think of the labs too much when I was prepping for the exams.”

When VJR observed the course in 2014, it included paper exams and module-based assignments. During that and the four preceding years, students would complete ungraded, Excel-based labs that were intended to help with the Excel and quantitative skills needed for the graded SSAC module(s) of the week. Beginning Fall 2015 with VJR as TA, the SSAC modules were reduced in number and replaced by more hands-on quantitative labs for about 2/3 of the lab time, and all lab activities were counted for course credit. Word problems were used more prominently and also for credit. None of the changes since 2013 are directly relevant to the interviews and are included only to complement the interviewees’ account of the evolution.

What interviewees remembered from the course, 1: Common themes. The exact question was, “Tell me what you remember from that course.” Note the emphasis here on the use of the word from, as opposed to about—that is, substance, experiences, and affect, as opposed to mechanics (which is the gist of the preceding section). Eight items were mentioned by two or more interviewees in response to this question or in the follow-up questions to it (Table 7).

Luke called CG “probably one of the most important, for sure” of his courses, and Sam explained that the course was partially responsible for the choice of
geology as a major. Jam said that specific events—discussed below—changed her life. Sunshine described herself as a “success story” from the course.

Table 7
What Interviewees Remembered: Common Themes*

<table>
<thead>
<tr>
<th></th>
<th>Important</th>
<th>Excel</th>
<th>Modules</th>
<th>Unit Conversions</th>
<th>Napkin, Back-of-envelope</th>
<th>Difficult</th>
<th>Polya Problem-Solving</th>
<th>Accessible/ Gender equality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medusa</td>
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<td></td>
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<td>×</td>
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<td>Jam</td>
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<td>Sunshine</td>
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<td>Gilda</td>
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<td>Luke</td>
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<td>Arya</td>
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<tr>
<td>J. Smith</td>
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<td>Sam</td>
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<td>J. Doe</td>
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<td>Lee</td>
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</tbody>
</table>

* “Common” means mentioned by two or more interviewees

Since the earliest iterations of the course, Excel spreadsheet calculations, and later, PowerPoint modules that guided them were used in class and in homework activities. All the interviewees mentioned the use of Excel in the course, with only Medusa—who took the course before the modules were introduced—not mentioning modules in some capacity. Jam took the course in the semester immediately before the introduction of modules but recounted her experience as a graduate student (and TA for the course) in helping to assemble and use the modules for the first time.

Almost all the interviewees—especially the regulators—mentioned unit conversions at some point in their interviews. Another common topic was quick estimation, also referred to as “napkin math” or “back of the envelope calculations.” Sunshine stated that,

I remember doing math on a piece of napkin that was Dr. Vacher’s goal for the class. That if you could sit in an airplane next to somebody and explain a math problem on a regular cocktail napkin, and you could draw a little diagram, that you were successful in his class.

Jam responded to the term “back of the envelope math” by saying, “yeah, I remember him using that phrase a lot.” Arya said that they use “back of the envelope stuff all the time, just estimating, getting a good, quick figure.”

John Smith described the course as “extremely challenging. But informative, and in the end a very beneficial course for me.” When asked to elaborate on how he found the course challenging, he said the following:
[The course] was meant to force you to think things through thoroughly. Think deeply. He always said think deeply about things. And at first I kind of just thought well, I always think deeply, how can you not think deeply? I got to know what he meant by that. You really do have to dig, deep to come up with the correct approach. There was sort of a multi-step process to everything we did in there. You needed to first analyze the question on a face value level, take in the whole thing, and then you kind of broke it down, and then from there, you could kind of start formulating a way to attack it, a way to approach it, and that was, in many ways, the most important part of it, because if you started out the wrong way, you’ll just end up going down a hallway and you’ll never get out, you’ll never get to the right answer.

This comment harkens to the four-step approach from How To Solve It (Polya 1957), which has featured heavily in the course throughout its time on campus. Polya’s method of problem solving involved the basic steps of (1) understanding the problem, (2) designing a plan, (3) carrying out the plan, and (4) looking back. John Smith’s quote here, although it doesn’t mention Polya by name, seems a solid reference to the first two steps of Polya’s plan.

Indeed, he was not the only person to refer to Polya, with others doing so by name. Jam said, “he was really big on Polya at that time,” and then recounted steps one, two, and, emphatically, four, which she uses with her students today. Lee mentioned Polya and described the method as “it’s so beautifully simple, and if you actually do it, it is incredibly helpful. If you actually do it. That was his entire course, was just learning how to think through things logically in a step-by-step manner.”

Medusa, Jam, and Sunshine—the first three interviewees, chronologically, to take the course—all made mention of the course giving a sense of belonging, accessibility, and gender equality not present in other geoscience and/or STEM courses they took at the time. Sunshine told a tale of a history of personal math avoidance, and her choice with three other women to take steps to overcome this tendency toward avoidance (elaborated under “individual perspectives”). Jam stated that as a product of the time she grew up,

No one ever said to me you’re a girl, you don’t do math and science, but it was implied everywhere. My last science class was 8th grade biology. And my last math class was 9th grade business math where I learned to balance a checkbook. And so girls didn’t do math and science. It’s in my head. Sometimes I still shake my head why I’m a geologist, because I’m a girl.

Medusa said

…and it was no longer, you know, girls can’t think in math terms versus boys it was let’s go get to it, and when you can really do this, then I’ll give you credence and we’ll move forward, and that was his only criterion for the most part.

What interviewees remembered from the course, 2: Individual perspectives. This section refers to comments made by individuals that were not repeated by
other interviewees, or which were so uniquely phrased as to place the response in its own category.

Lee—who took the course most recently among the interviewees—emphasized the real-world connections:

He was always really good in his exams about bringing applicable situations to when you would actually use this method or this particular topic, and so that was nice. It wasn’t just, here’s something, figure it out this way. It was asking you to actually go through things that you have learned in the course and decide what would be the best approach to figuring out the problem. And it was a real-world approach and that was, that was really nice.

John Smith compared requirements from the course that later became applicable to his career, in particular.

Up to that point I had no idea how to convert between a hectare and an acre, for example, and by the end of it I could do it in my sleep. There was all kinds of just great information embedded in it. That he just expected us to just know. I mean, it was our responsibility to learn that stuff and know it and have it locked down. Because at the end of the semester, when the exam comes around, he’s not telling you what the diameter of the Earth is. He’s not telling you the conversion factor between one thing and other. That’s your responsibility to know that. And that’s something that really carries through to the professional world. There’s all kinds of stuff like that, that you just have to know. You can’t always look in your book, you can’t always Google something, you’ve got to know what you need to know to do the work, and that’s something he taught me in that class, and something he really grilled into us, is learn these basic building blocks of things, because you should know them, there’s no reason not to know them. So, in that sense, I took a lot from it with me, things that didn’t seem important to me at the beginning, and then at the end there’s all kinds of stuff like that.

Sunshine described how she came to grips with the course.

I became really good friends with some ladies in the course. So if anybody has met Vacher, he can seem very unapproachable at first, and not relatable. So there’s four of us. We did not succumb to Dr. Vacher’s intimidating aura, so we sat in the very front row. All four of us in the front row. Everybody else sat back behind us pretty far back. We wanted to learn. We wanted to hear what he had to say, and the only way to truly be successful in his course was to be involved and to be connected to Dr. Vacher, to be able to stop him whenever you have a question or be able to ask him to elaborate. So we sat in the front row and we asked him questions all the time… he was not used to that. And all four of us are still very good friends.

And, she added a story regarding an experience that improved her personal confidence.

I was always kind of a math avoider, and I remember we had this one problem about a meteor impact, and we were looking at the blast radius, so we were looking at trying to figure out how big the meteor that hit, based on the crater that it produced and then the ray around it. And I remember because I’m still proud of myself because I actually answered a question and I answered it correctly. He asked the students “OK, now, what are some of the measurements of the… the impact that we could use to figure out how
big this meteor was?” And no one was saying anything. And I’m like, well, this seems pretty simple to me, so I raised my hand. And he was like “Sunshine”. So I said “um, well, can’t you just measure the length of the ejecta? And figure out how fast it was coming that way?” And his face, like, lit up when I said that. I was almost cause now that that I’m a professor I know what he felt, like, she got it, she gets it! You’ve got to critically think about something. How can you look at a problem and figure out the answer that you need to from the data that you’re given? I remember that being a defining moment for me. And the rest of the class looked at me like, how did you get that?

Jam also told an extraordinary story relating to an experience in the course that shaped her future.

It was probably the first day of class. He taught about I don’t even remember about what. But as I was leaving the room, I walked up to Dr. Vacher, and I said, “I just want you to know I don’t do math.” And he looked at me, and he didn’t respond as far as I can remember. And he just let that go. I was very proud of myself for saying that, because this is the course that nobody wanted to take. Everybody was afraid of him. A little while into the semester I could hardly wait to get home every day to do the homework. It was the first time in my life I was ever successful at doing any kind of a math problem, a word problem. The homework, Excel stuff. And about, I’ll guess a month into the semester, he asked me if I remembered what I had said to him the first day. And I turned red and said “Yes, I absolutely remember that”. And he said, “You know, [Jam], if you weren’t able to read, you would have been so embarrassed about that that you would never have told me or anyone else. You should be just as embarrassed to have said you weren’t quantitatively literate.” And that statement changed my life.

When asked, on follow-up, about how this experience changed her life, she explained that it made her want to be quantitatively literate. Jam further described that this goal led to a persistence, saying

I would struggle with the homework, but I would sit there and do it until I understood what I was doing. I would do the math problems and be in awe of myself when I got an answer in the back of the book that matched.

Jam later discussed how she learned more, conceptually, about what calculus and other forms of math really meant and why they were used, in just a few minutes in the course than she had in entire semesters of standard math courses.

Somebody says the word logarithm and I say, yeah, man, he made it so clear. And I’ve said this to him, I’ve said it to current and former students in his class, and I’ve said it to people outside of USF. I really felt like I learned more in a ten minute discussion in his class about calculus than I learned in two semester sitting in calculus math class here at USF. At the end of those two semesters [of engineering calculus 1 and 2], I didn’t know why you do calculus. I never got that a derivative was the slope of a line and that the integral was the area under the slope. Two semesters, I never got that. I learned how to take letters and numbers here, and then there was the equal sign, and I had learned how to change those same letters and numbers and make them different over here. And I could do it. I think I got an A or A– in calculus, which I was like, how did I do that? I didn’t understand it at the end. And in ten minutes, when he explained this is what a derivative is, all it is is the slope of a line, oh, the light came on. And… you don’t hear that in a
math class. At least if you do, I wasn’t paying attention that day. If they ever said a
derivative is the slope of a line? I completely missed that.

Medusa—whose early iteration of the course involved a relatively large
amount of calculus compared to later sections—described something similar
regarding geology, math tools, calculus, and confidence.

The course allowed me to see mathematics as a tool that I can realistically use in the
applications of geoscience instead of viewing calculus etc. as a separate thing from
geology. And it took the fear away. It was a very common theme at the time that folks
felt challenged by a lot of the math courses that they were in. They were having trouble
with them. Some of them were even failing them. When these concepts really are quite
central to geology. And Len saw them as central, didn’t understand why we weren’t
functioning within both equally well, so he looked at how those courses are being taught,
and how geologists think, and created a course that took the fear out of math, which is
huge.

When asked how this was accomplished, she responded as follows:

Well, he answered what I call the primary questions. Which actually may be a concept I
got from Len, I don’t remember where I got it; it very well could have been Len. Primary
questions being “so what?” and “who cares?” So he went back to relating to the concepts
that geologists work with every day. You know, a derivative is change over time, that’s
all it is. Geology is change over time. Almost everything we look at in geology is change
over time. Until he said that to me, in that sentence, I had never seen it, I had not seen a
derivative that way, and I had not really applied, oh, that’s why I might want to use that
in geology. Why the mathematics and the computations are so inherent in the application
of geoscience. He firstly made it relevant for us, and secondly, was able to get to the nuts
and bolts of how you use it instead of just fluttering about with the theory that a lot of the
courses were doing. This is more physics than calculus, but a ball’s coming at you at a
certain angle, and if somebody hits the ball, how’s it going to go? Well, you know, in my
mind, the answer to that was ‘home run’. The nitty gritty of that didn’t matter to me, and
Len was able to help me understand exactly why I would want to know that. And why I
would want to use these tools to get there. So he made it a tool that I can use, and made it
something I wasn’t afraid to use, and made it something I was excited to use and felt
empowered by instead of somewhat fearful of.

What interviewees mentioned was useful from the course, 1: Common
themes. The exact question was, “Is there anything from the course that you used
professionally or personally since graduating? Seven items were mentioned by
two or more interviewees in response to this question or in the follow-up
questions to it (Table 8).

Several alumni, speaking in a general way, stated that they use the material or
learnings from the course on a daily basis. Lee, when asked this question, said,
“every day… every single day.” She later elaborated by saying,

I use Excel. I use computations every single day, and it was really eye-opening to get to
grad school and to see it, the focus was way more on computation than I ever gathered
when I was at USF.
John Smith responded to the question by saying,

definitely the Excel work. For sure. Every day of my life I live and die in Excel at my job.

<table>
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<tr>
<th>What Interviewees Mentioned as Useful: Common Themes*</th>
<th>Excel</th>
<th>Their notes</th>
<th>Modules</th>
<th>Weighted Averages</th>
<th>QL/Thinking</th>
<th>Unit Conversions</th>
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* “Common” means mentioned by two or more interviewees

The specific statement that Excel/spreadsheet work was commonly used was universal, one way or another. In fact, only Arya did not specifically mention using Excel, although she later said graduate students need to know how to use it well (and we know independently that she uses it in her dissertation research all the time). John Smith, one of the consultants, went on to say,

I’ll write my reports with pen and paper if you want me to, but if you take Excel away from me, I’m dead.

Luke, one of the regulators, referred to reviewing the Excel sheets submitted for permits, and the knowledge for the course helping him to understand what he sees:

I learned a lot about Excel; I can look through a sheet and reverse engineer it, find out the calculations, things like that, that people have submitted to me.

John Doe mentioned Excel for both professional and personal purposes, saying,

I’m always pulling up Excel, and doing some statistics on financials or stocks, or anything that I’m interested in.

Sam said,

Yes, I definitely use Excel in my personal life for maintaining finances.
Both Arya and Lee mentioned that they still have all their notes and labs from the course and refer back to them frequently. Referring to both the computational geology course and a somewhat similar graduate-level QL-in-geology course titled Math Concepts for Professional Geologists, Arya said,

I still have all my notes from both those classes and I actually still refer back to them. I’ve used my notes for other classes just to look at like vector algebra or something like that, that’s sometimes I don’t memorize those things, I have to go back and review.

Lee, another PhD student, expressed it similarly, saying,

I actually still have all the labs and all our lab exercises just in case I forget exactly how to do one thing.

Sunshine and Arya mentioned using the modules in teaching, and Jam mentioned the use of Excel and the tutorial modules in her teaching as well. As a graduate student working with both HLV and the course TA at the time, Sunshine remembered,

We actually created pre-modules to the modules, to help students that go, ok, this is what a module is about, this is what Excel is about, these are the equations that you could be using in Excel. So kind of a, let’s get the students up, all on the same playing field, before we just throw this complicated module at them and possibly they don’t even understand the quantitativeness (sic).

These “pre-modules” she mentions here are tutorial modules that are still used in the CG course and in several other courses as preliminaries for the Excel work within the courses.

Two interviewees mentioned using averages frequently. Arya has a history of study and teaching in sedimentary geology, which includes the topic of grain size distribution in sediments. She discussed the need to use (and teach) weighted averages to determine the mean grain size of sediments. John Smith said,

Well, we’ll go to averages. There’s different kinds of averages, and they do different things for different reasons, you know? There’s a right time to use an, um, arithmetic mean. There’s a right time to use a geometric mean.

Several interviewees referred to using QL specifically, or to the skills under its umbrella without using the actual QL label. For example, Luke said that the course

… made me think about (the math I already knew) a little bit differently.

More explicitly, John Smith stated,

Quantitative literacy is one of those… it’s a life skill. Once you learn it you can’t unlearn it.

Jam, after stating that she makes her students in introductory geology do Excel exercises, said,
I want my students to be quantitatively literate.

Sunshine mentioned working unit conversions and other aspects of QL into her courses in introductory geology.

I ask questions at the end of the lecture. Along the lines of quantitative literacy.

Unit conversions were mentioned specifically by Luke, Sam, Sunshine, Gilda, and John Doe. Sunshine mentioned them explicitly in the context of the QL questions she asked in her classes,

I do your stereotypical assignment of unit conversions.

Sam’s primary response to the question gave an intrinsically fundamental geological point of view:

One thing that I definitely do on a regular basis is convert from elevation, height above sea level or something, to feet below land surface.

Gilda added unit conversions as the second item she used frequently (after Excel), saying,

And unit conversions, that probably helped a lot too.

John Doe mentioned unit conversions in connection to proportions,

I’d say that proportions I use a lot, and on the other end of that is unit conversions.

The topic of unit conversions came up in answer to more than one question in Luke’s interview, with him saying in response to this question,

I hate to keep going back to unit conversions, but that’s definitely something that was really stuck in my mind, to make sure you do them right.

John Smith, Lee, Arya, and Medusa, discussed using statistics, or at least statistical literacy, in their professional or personal lives. John Smith asked,

Are you introducing statistical error by setting up a certain way?

Lee said,

I use the statistics that he went over all the time.

Arya completed an MS thesis that used computers to perform detailed statistical analyses on beach sands. In discussing how the computational course had given her a foundation for this work, she said,

I felt like it gave me a little bit more of a starting point because I was not very strong in statistics, so with not having a strong statistical background and doing a thesis that’s just highly related to statistics was very stressful but I was able to go back and use my notes to help me along with just doing the basic mathematics that were needed for that.

Medusa had a particularly interesting and personal way of expressing the relevance of the subject to her,
I don’t seem to express myself or learn in ways that fit, you know, that are within one standard deviation of the mean.

She went on to express how she explained to her son his differences and exceptional abilities in terms of standard deviations and the population mean, and said,

And having been through a course like Len’s allowed me to see the concept so simply, instead of it being this weird calculation that I’d have to work really hard to be able to function with. It’s a very basic concept to me, and it’s now a very basic concept that my son uses every day to perceive himself. That’s a big deal.

What interviewees mentioned was useful from the course, 2: Individual Perspectives. This section refers to comments made by individuals that were not repeated by other interviewees, or which were so uniquely phrased as to place the response in its own category.

Sam directly linked the course to her ability to maintain personal finances using Excel.

I have spreadsheets of how things are moving and where money is going and all kinds of things like that, and I probably would not know how to do a lot of that stuff if it had not been for that class.

Gilda, like many of the interviewees, took both the computational geology course and the similar graduate course titled Math Concepts for Professional Geologists. She related one use that was relevant in her life that she learned in both courses (part of Polya’s first step).

If there’s ever any sort of question, I’ve gotten used to drawing a picture and labeling everything in order to better understand what to do to solve it.

John Doe said something regarding how the course changed the students’ thought processes about some terms that reflected a clear habit of mind consistent with QL.

I think what the course did was make us wary of statements like “greater than” or “percent more.” Dr. Vacher has a very strict policy on using certain phrases to describe something, so description of percent more should mean percent more than and that was actually a small segment of his course, so I think what it made us, what it makes me do is when someone says something like that or a statistical phrase, I think about it and say, “is that what they really mean,” because I know mistakes are made all the time.

Arya served as an unofficial course TA and used her knowledge of course modules to help write introductory text documents for students that were intended to assist them in getting through unfamiliar terms or processes. “So I would just, I would use my previous, experience to help the students.” She also mentioned having used certain math skills from the course in her current occupation as a graduate assistant. “Matrix algebra is a big one and that has helped me I use a lot of vectors.”
In discussing quantitative literacy in depth, John Smith related QL to his personal life.

It [QL] sort of pervades everything. So it has impacted my personal life, for the better, of course, but things like that. I’ll go into the store, I’m trying to get a deal on lemons I’ll go, what’s the price per ounce here? Should I get the big lemons or the small lemons; get the bag of lemons or should I buy them individually? And the wheels start turning automatically now, whereas I used to just, oh, $2, $1, I’ll get the $1 bag? But stuff like that happens all the time. I’ve become a more analytical person because of it.

Lee is in graduate school studying oceanography, and

I manage a large data set. I try to apply numbers to things that I’m doing every day.

When discussing specific skills she uses frequently from the computational course, she stated

I use percent differences and the statistics that he went over, Excel formulas and arrangements all the time.

She suggested that a significant purpose of the computational geology course was to help

not be overwhelmed by the numbers.

Although the use of Excel itself was by no means unique to her, Sunshine had a couple of good stories on how she put Excel to good use. The first was to convince her husband to buy a car:

Well, ever since that course, I have used Excel. I never really used Excel before it, and I love Excel now. I use it for everything. I used it for my chemical data that I collected for my rocks for my master’s. I used it to create my budget for my house for my husband. I used an Excel spreadsheet to show my husband that we needed to trade in our other car and buy a new car because it was going to be gas efficient and we were going to save money. And when I did the Excel spreadsheet for convincing my husband to buy a car, I made the spreadsheet up and I had the amount of what gas would cost as a variable, the amount of miles he was traveling, what miles per gallon for each car we were thinking about buying. Then comparing that to what we were spending right now with the car that he was driving, so looking at gas and tolls and then comparing that to how much it would cost, how much it would save us if we bought a new car that was gas efficient, but we had a car payment, but the car payment was still, the car payment plus the gas was still lower than having a car that was already paid off but horrible gas mileage. And I made a whole spreadsheet that he manipulated and played with all these different variables and it changed the bottom number to figure out how much we would save every month. And that convinced him, and we went and bought a new car.

The second was to explain to a student how to pass her course.

Last week I made an Excel spreadsheet for one of my students who was going to fail. And I created an Excel spreadsheet of the labs she has turned in, the quizzes she has turned in, and I color coded the cells for the ones that she could manipulate to see what she would need to get on the labs and the quizzes to get the grade she wanted at the bottom. So at the bottom I had her weighted grade calculated so it would change
whenever she changed those cells. And that’s all stuff that I learned from computational geology.

Sunshine additionally spent time in graduate school employed by HLV organizing the modules over summers, and later wrote a module which is on the Science Education Research Center14 (SERC) website. She uses the modules in her current teaching assignment to help students learn QL in geology.

Medusa, the interviewee with the longest perspective, had the following to say about how she has used what she learned in the course.

M: Almost all of it. Um, now I can’t say I that I actively…

VR: Can you elaborate on that?

M: Sorry, I don’t know that I actively, I mean, I don’t actively do these calculations any longer. I, you know, I don’t actively write out these equations, however, the work I do…

VR: Now why would that be?

M: Um…

VR: Is it because of the computer does it, or because you’re above the level in the company?

M: Several reasons. Both. Now I’m not the person who does the technical aspects as much anymore; I’m more of a project manager, and person who does design for projects. So when I need calculations run, I have folks that do that. And of course we have models that we run; however, I make folks go back and show me that they can do the calculations if they’re going to be running the model. One of the strongest things that we learned from this course was that you can make a model do anything. And things have to be able to pass the smell test. It has to make sense. It has to be valid. You can make a model do anything based on the inputs but unless the math is solid, the calculations are solid, the model is meaningless. Again, so what and who cares? Why did I run this model? I would say I use the information that I learned in his class to vet the validity of models that I see every day. I did that as a regulator, and I do that now.

**Subjectivity and reflexivity**

It is appropriate in qualitative research to pause and consider “What is the researchers’ impact on the research process, what kind of stimulus do they constitute for research participants, which interactions take place between the researcher and the research participants, and what is their outcome?” (Mruck and Breyer 2003). It is certainly true that this case study is anything but objective, particularly in the fact that one of the course instructor’s current graduate students is the principal investigator of the qualitative research, and the instructor was so much in the background as a part of the contextual setting (even to the extent that most of the interviews were in the principal investigator’s office, which is the instructor’s lab).

14 The Science Education Resource Center, housed at Carleton College, [http://serc.carleton.edu/index.html](http://serc.carleton.edu/index.html)
The study is strongly biased on account of the study population. On the other hand, the study was not intended to be representative of the general population of students who took this course over the twenty years of its existence. This lack of random selection constitutes a selection bias. The use of a selection-biased population allows future studies—including possible surveys to representative alumni populations—to feature well-researched questions based on the experiences of the selected, professionally successful interviewees in this study.

Additionally,

• Professional success was entirely in the opinion of the course instructor, and was not based on rigorous testing of any sort.
• Convenience sampling was used due to lack of funds (9 of 10 interviewees were local at the time of the interview).
• Confirmation bias was noted in some follow-up questions (phrasing of questions that shaped possible answers in a specific way). Where noted, these responses were not used for quotations in the text.

Lastly, all interviewees (as well as the interviewer and first author of this paper) were currently or formerly connected to the course instructor (the second author) through letters of recommendation, post-graduate work, or alumni activities. Unsurprisingly, a significant proportion of interviewees felt they owed some debt of gratitude for their position in their career to the course instructor for his teaching, assistance, and guidance in and out of the classroom. (Some expressed this feeling on record, while others have discussed it informally). Although this study is not about any one person, it must be acknowledged that there is an inherent reciprocity in the selection bias mentioned above in that these interviewees are highly unlikely—even given anonymity—to say anything particularly critical of the instructor or the Computational Geology course. This lack of criticism should not be taken as evidence that negative views don’t exist; in fact, the second author knows that they do.

So What?

It is gratifying to see that Medusa remembers the “so what?” question. If indeed she did get it from her Computational Geology course nearly 20 years ago, it is worth passing on again the ultimate source: a widely shared editorial for students from a renowned researcher of reefs in Florida and on Earth (Ginsburg 1982, 351),

“‘So what?’ stands for a family of questions or an attitude that leads to consideration of the broader significance of specific studies. These kinds of questions are particularly useful in descriptive research because, often, one can get so absorbed in collecting, organizing and analyzing observations one forgets to consider the implications of the results.
The “So What?” of our descriptive case study follows from its three-pronged setting:

1. It occurs within a time in which institutions, programs, and courses in higher education seek to distinguish between outputs (productivity) and outcomes (what students take away) (e.g., Dugan and Hernon 2002). For our GLY course, the intended take away, clearly and emphatically, is QL.

2. The Association of American Colleges and Universities specifically lists QL (along with information literacy, problem solving, critical thinking, creative thinking, ethical reasoning, and global learning, among others) as essential learning outcomes (AAU&U 2007; see also Vacher 2011).

3. Madison’s question (Madison 2001) still resonates: Who in the academy has responsibility for QL? Our answer to Madison’s question is that the disciplines share in the responsibility. QL as a learning outcome is not solely the mathematicians’ responsibility. That belief energizes our course, and it motivates this paper.

Broadly within the discipline of geology, there appear to be three approaches to building the QL of our students:

1. “Integrat(ing) quantitative tasks into courses to illuminate students’ understanding of geoscience, as well as to enhance their quantitative skills” (Macdonald et al. 2000, as quoted in our Introduction). (For Numeracy papers, see also Wenner et al. 2009, Lehto and Vacher 2012, and Wenner and Baer 2015).

2. Requiring majors to take geology electives that stretch them mathematically while sharpening their problem-solving skills (as in the “quantitative requirement” in GLY at USF noted in the background section; see also Connor and Vacher 2016).

3. Offering a course within the discipline in which QL coupled with problem solving experiences is the framework and substance, while the geology provides supporting and motivating material.

Clearly, the Computational Geology course of this paper is an example of the third approach. As far as we know, it is the only example. Therefore, it is incumbent on us to ask from the alumni interviews: What values can we say that these alumni of Computational Geology took away from the experience?

On the notion of values, we draw on a study by Norris et al. (2014) of a kindred literacy as an educational goal. In that study, a Google Scholar search using “scientific literacy” produced 62 articles published since 2000 that either classified or justified the objectives of scientific literacy. According to those researchers (Norris et al. 2014, 1320),

... we find it valuable to categorize the proposed outcomes of scientific literacy into three categories of values: values regarding the states of knowing one might obtain, values regarding the capacities one might refine, and values regarding the personal traits one might develop. We call them all values because they refer to ends of science education that are judged desirable.
With a framework, then, of (1) states of knowing, (2) capacities, and (3) traits (Norris et al. 2014) as a guide, we can list some of the takeaways that some of the interviewees expressed – in their own words:

1. States of knowing one might develop, such as understanding and knowledge (e.g., facts and concepts)
   - Facts: Conversion factors
     * He’s not telling you the conversion factor between one thing and another... that’s your responsibility to know. And that’s something that really carries through into the professional world. – John Smith
   - Facts: Excel functions
     * I think I have probably used every single Excel function that Dr. Vacher showed us. - Gilda
   - Facts: Orders of operation
     * You have to know the order to do the calculations in or else you’re going to be wrong – Arya
   - Concepts: Percentage
     * What the course did was make us wary of statements like greater than or percent more. – John Doe
   - Concepts: Logs
     * ...the log scales ...I really remember a lot, because that stuff I have trouble with... -- Arya
   - Concepts: Logic as a process
     * That was his entire course, was just learning how to think through things logically in a step by step manner. – Lee
   - Concepts: Calculus is geological
     * A derivative is change over time, that’s all it is. Geology is change over time. Almost everything we look at in geology is change over time. – Medusa

2. Capacities one might refine, such as abilities (skills)
   - Communication:
     * If you could sit in an airplane next to somebody and explain a math problem on a... cocktail napkin, and you could draw a little diagram, you were successful in his class. – Sunshine
   - Excel
     * I learned a lot about Excel... I can look through a sheet and reverse engineer it, find out the calculations... that people have submitted to me. – Luke
   - Unit conversions
     * Converting, you know, from different units and that sort of thing. – Sam

3. Traits one might develop, such as dispositions
   - Problem solving
     * The relevance for my everyday job would probably be using the same problem solving skills that we learned... I’m never going to have to try to solve the same exact problems he presented, but I can use the same steps that he showed us in order to solve whatever I might run into. – Gilda
That class really instilled in me a sense of...thoroughness....There’s always something lurking in the shadows that you need to address...when a problem comes up. – John Smith

- Confidence
  He made it a tool I can use, and made it something I wasn’t afraid to use, and made it something I was excited to use and felt empowered by instead of somewhat fearful of. – Medusa

- Analytical thought
  I’ve become a more analytical person because of it. – John Smith

- Quantitative literacy
  I want my students to be quantitatively literate. – Jam

Returning to the “So What?” of Ginsburg (1982), then, we can state the broader implication of our specific study: We have an example here (“an existence proof,” as Madison might call it) of a long-standing and still-cranking, standalone QL course for upper-division, in-discipline majors in a STEM discipline. Thus QL can be developed—and indeed welcomed in the home discipline—in a course not taught by mathematicians.

It is important to underscore an additional observation. The QL takeaways of our interviewees are basically the same from the era of Medusa (in 1997) and Jam (2001), when the evolving Computational Geology was in its more mathematical literacy stage, to John Smith (2011), John Doe (2012) and Lee (2013), when the evolution had taken the course unabashedly into the domain of traditional QL. The common element throughout the story was problem solving. In other words, the type and level of the mathematics didn’t matter. It is the context that makes the course go and gives it legitimacy for the people it serves.

**Concluding Remark**

Returning to Madison and “Everybody’s Orphan,” it would be unfortunate if the need to pitch in and adopt the orphan would be seen as a burden. After our experiences teaching Computational Geology (2 years and 20 years, respectively), we can attest that the subject is a pleasure to teach. Probably the biggest reason is that we are at home with the context, which gives us common ground with our students. A second reason is that an amazing proportion of our students have had bad experiences in prior math encounters. To the extent that we can use their positive attitude about geology to discover their mathematical selves by recognizing the beneficence of mathematics as a way of doing things that matter to them (“a tool I can use,” said Medusa, perhaps quoting the textbook she used in the course, Waltham 1994), and they find that now this math stuff does make sense after all—teaching QL in the discipline thus becomes its own reward.
Acknowledgments

The qualitative research reported here was part of VJR’s MS thesis (Ricchezza 2016), and we thank Jeff Raker and Jeff Ryan for their guidance as proactive members of the thesis committee. We thank the three Numeracy reviewers for their helpful comments, all of which led to substantial sharpening and clarification. HLV thanks the successive departmental chairs (Mark Stewart, Chuck Connor, Jeff Ryan, and Mark Rains) for their support of the course and their belief in the value of QL for geology majors. Finally, words cannot express our gratitude to the more than 300 students for their forbearance and the ten interviewees for their generous contributions to our study.

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### Part B. Spreadsheet modules


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Quantitative Literacy in the Affective Domain: Computational Geology Students’ Reactions to Devlin’s *The Math Instinct*

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Quantitative Literacy in the Affective Domain: Computational Geology Students’ Reactions to Devlin’s *The Math Instinct*

**Abstract**

Building on suggestions from alumni from a recent interview project, students in Computational Geology at the University of South Florida were tasked with reading a popular non-fiction book on mathematics and writing about the book and their feelings about math. The book, *The Math Instinct* by Keith Devlin, was chosen because we believed it would give the students something interesting to write about and not because we had any expectations in particular about what it might reveal about or do for their math anxiety. The nature of the responses received from the students led to the performance of a post-hoc study on the emotional affect of math in the students’ lives and how it changed as they proceeded through the book and reflected back on it at the end. Of the 28 students in the fall 2016 section of the course, 25 had an improved or slightly improved attitude toward math by the end of the semester. The assignment was more successful than we could anticipate at generating thought and getting students to communicate about math – an integral component of quantitative literacy. Although the limited size and post hoc nature of the study make it difficult to generalize, the results are promising and invite further use of the assignment in the course.

**Keywords**

Affective Domain, Math Anxiety, Qualitative Research, Math Education, Geoscience Education, Student Writing

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**Cover Page Footnote**

Vic Ricchezza and Len Vacher are a doctoral student/teaching assistant and professor, respectively, in the Geology program in the School of Geosciences at the University of South Florida, Tampa.

This notes is available in Numeracy: [http://scholarcommons.usf.edu/numeracy/vol10/iss2/art11](http://scholarcommons.usf.edu/numeracy/vol10/iss2/art11)
Introduction

In this note, we detail and discuss our observations from a post hoc study conducted in our quantitative-reasoning-in-geology course. This study reviewed student submissions from a reading/writing assignment that was given as a sidelight to the students’ work on geological-mathematical word problems. We asked whether students’ disposition toward math changed after reading *The Math Instinct* (Devlin 2005).

**Quantitative Literacy in the Affective Domain**

The meaning of “quantitative literacy” (QL), “quantitative reasoning” (QR), and “numeracy” is a recurring topic in *Numeracy* (e.g., Vacher 2014; Karaali et al. 2016). Despite any disagreement on the finer distinctions between these terms, however, some basic connotations and uses seem near-universal. One such commonality is exemplified by Madison (2006, p. 2323): “QL is a habit of mind rather than a content-rich academic discipline.” But how can a “habit of mind” be studied, discussed, and taught? Surely, attitude and affect come into play. To clarify in this context what we mean by *affect*, we are referring to the *affective domain* (Krathwohl et al. 1964) of educational psychology as the branch dealing with emotions and feelings (as opposed to behaviors or thoughts).\(^1\)

We have noted an apparent trend when reading articles on QL instruction: the articles concentrate mostly on the cognitive domain, while expending less effort on any emotional component. But our students are not unemotional automatons. Quite to the contrary, over the 20-plus years that the Computational Geology (CG) course has been offered at the University of South Florida (USF) (Vacher 2000; Ricchezza and Vacher 2017), it has become quite obvious that many (if not most) of our students have an emotional, at times visceral, response to mathematics.

Our experience is by no means unusual. As noted by (Hart 1989, p. 38), for example,

> It is relatively clear that decisions about how many and which mathematics courses to take in middle school, high school, and college can be influenced by affective characteristics of the student that have developed over many years.

This view is supported by studies indicating that a student’s experiences with mathematics in 7th - 10th grade classes influenced how they performed in mathematics in the 12th grade, which in turn influenced whether they chose to be a science, technology, engineering, or mathematics major in college (e.g., Wang 2013). The choice, in fact, may be due to how mathematics is taught and used in the United States (e.g., Follette et al. 2017).

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\(^1\) [http://open.lib.umn.edu/socialpsychology/chapter/1-2-affect-behavior-and-cognition/](http://open.lib.umn.edu/socialpsychology/chapter/1-2-affect-behavior-and-cognition/)
Student emotions regarding mathematics noted in prior interviews with CG alumni reported in Ricchezza (2016) range across a wide variety of attitudes about math education, math practice, and even basic situations where mathematics make unexpected appearances. These attitudes (among CG students) vary from the most positive and enthusiastic to extremely negative and math avoidant. Indeed, while our paper focuses now on the breadth of feelings and emotions evoked by a new, semester-long writing assignment in CG, our attention at the time of implementing the assignment was not focused specifically on math anxiety or math avoidance but rather on improving the students’ communication skills when discussing mathematics. However, once we read the responses, math anxiety and math avoidance – i.e., math in the affective domain – came to the fore.

The phenomenon of math anxiety should come as nothing new to the readers of this journal. Math anxiety can be described as “a feeling of tension, apprehension, or fear that interferes with math performance” (Ashcraft 2002, 181); it is only weakly related to overall intelligence, but leads to an avoidance of math activities by those afflicted with it. Thus the math-anxious predictably achieve less in math relative to those who do not suffer from math anxiety (Ashcraft 2002).

Indeed, more specifically regarding numeracy, math-anxious individuals perform poorly relative to their own apparent thinking and reasoning ability in non-numerical tasks (Maloney and Beilock 2012). Maloney and Beilock go on to state that this anxiety may develop early in education – as early as elementary school. A pattern of brain activity is associated with negative emotions and numerical computations in those affected, and teachers can pass along negative attitudes to their students. However, “when anxiety is regulated or reframed, students often see a marked increase in their math performance” (Maloney and Beilock 2012, 405).

Some articles published by this journal demonstrate this ability to mitigate math anxiety through modest teaching innovations (Wismath and Worrell 2015; Lipka and Hess 2016; Follett et al. 2017). Of course, not all such interventions produced the desired results (Sundre et al. 2012; Mayfield and Dunham 2015).

In “Twenty Questions about Mathematical Reasoning,” Steen (1999a, Question 10) asks “Does ‘math anxiety’ prevent mathematical reasoning?” Steen gives the short answer, “yes… sort of” – what students fear is not mathematics so much as how it is presented in schools. Indeed, in “Reading, Writing, and Numeracy,” Steen (2000) lists one of the goals of numeracy or QL as “reduced anxiety: diminishing the negative effects of school-grown ‘math anxiety.’”

A quick literature review found three Numeracy articles relating specifically to math anxiety and math avoidance. A QR course at Seattle University (Henrich and Lee 2011) used “service learning” (making students into tutors, essentially) and studied the effect on student attitudes toward math and math anxiety; results indicated clear improvements. A survey (Wismath and Worrall 2015) of a Canadian university QR course (discussed earlier in Wismath and Mackay 2012) found strong
improvements in self-reported student attitudes toward their own math abilities and toward perceived math anxiety. A study on math anxiety at Portland State University (Latiolais and Laurence 2009), expanded to math avoidance, led to two different course-type offerings specifically to help math-avoidant students find help. Other examples can be found over a wide range of other journals, such as *Childhood Education* (Furner and Berman 2003), *Journal of Research in Mathematics Education* (Ho et al. 2000), and *Journal of Counseling Psychology* (Betz 1978).

**Course Background**

Computational Geology (CG) is a QL-in-geology course at the University of South Florida (USF)\(^2\) and has been a fixture in the geology (GLY) major there since its initial offering in 1996 (Vacher 2000; Ricchezza and Vacher 2017). The CG course came about because many students – most notably from the ranks of the so-called nontraditional students, i.e., students who were restarting their education after various life experiences – realized that they did not possess the mathematical skills they would need to obtain and perform the jobs they sought (Vacher 2000). The second author (LV) created the course and was its sole instructor during 1996-2015, and he has taught it in alternation with another professor since 2016, when the course went from a once-per-year offering to twice-per-year. The primary author (VR) has been the graduate teaching assistant (TA) for the course since the fall 2015 semester and completed a qualitative study of the course featuring interviews with alumni spanning the course’s history (Ricchezza 2016).

The course has undergone significant changes in instructional methods and content over its two decades (Ricchezza and Vacher 2017). From the beginning, CG has consistently been heavy on using spreadsheets to teach geological-mathematical problem solving (Vacher 2000; Vacher and Lardner 2010) and is now near obsessively focused on geology-context word problems. In the early years, the course was seen as a capstone to the GLY department’s requirement of a year of calculus. It soon evolved to what LV considered a QL course emphasizing material that the geology students had missed – for a variety of reasons – in their mad path to calculus (i.e., GATC). Operationally for the course, he came to think of QL in terms illustrated by the course-contemporary slide shown in Figure 1. Note, according to this portrayal, QL is antipodal to math phobia, anxiety, and avoidance.

\(^2\) USF is a multi-campus public university, with the main campus (42,000 students) set amidst the northern urban sprawl of Tampa, Florida (http://www.usf.edu/about-usf/facts.aspx). The Carnegie Foundation for the Advancement of Teaching classifies USF as both a Doctoral University with “Highest Research Activity”(RU/VH) and a “Community Engaged” institution (http://news.usf.edu/article/templates/?a=3070). USF is home to many non-traditional students, including returning military veterans, two-year college transfers, and students returning to school after long absences. The CG course aims to prepare geology majors for more-advanced geology courses involving math and for success in the workforce.
Not surprisingly, the subject of math anxiety was brought up by some of the alumni interviewed by Ricchezza (2016).

The interviewed alumni were also asked about what they thought today’s students should be learning now that would help them succeed professionally after graduation. Several stated that written communication skills were vital, and they noted that such skills were lacking in many of their recent hires (Ricchezza 2016). Remembering that effective communication of arguments using quantitative evidence is a primary component of QL (Steen 1999b), and that a course designed for QL and/or QR “requiring students to write responses promotes clearer thinking” (Madison 2014), we added a writing assignment to the course for the fall 2016 cohort. The addition of this writing assignment was in response to the alumni suggestions from prior studies and was for course improvement. No thought was given beforehand to our writing a paper on the experience. After the data were collected, however, it became apparent that what we had collected was of such interest that we would be wasting a valuable opportunity if we did not perform a post hoc study based on the collected data.
Methods and Approach

All 28 students in the fall 2016 CG course section were given, as a normal component of their coursework, a reading/writing assignment that constituted 10% of their final course grade. Students were also assigned to write a series of word problems for another 10%, but the word problem assignment was not new for the fall 2016 semester and was not considered for this study. Writing submissions were graded for completion (all grading of writing assignments was done by LV); feedback was largely concentrated on encouraging the students to push through difficulties, with occasional commentary on major lapses in grammar, spelling, or attention to detail. Writing submissions were handed in through the online course-management software provided by USF, with text entry for all items except the final assignment, which required students to upload a one- to two-page document for plagiarism checking.

Students were asked during the first week of class to give “a two-paragraph statement describing what [they] think of [their] experience with mathematics and [their] attitude toward the subject.” Students were then required to read The Math Instinct: Why You’re a Math Genius (along with Lobsters, Birds, Cats, and Dogs) (Devlin 2005). At the conclusion of each week (starting week 2), students responded to a chapter of Devlin’s book until the 13th/final chapter was finished in week 14. Students then submitted a final assignment – a one- to two-page statement in response to the following prompt:

…[D]escribe what you got out of the book. Recall what you wrote in the first assignment, which was "a two-paragraph statement describing what you think of your experience with mathematics and your attitude toward the subject.” Has anything changed in that regard as a result of your experience with that book?

After submission of the final assignment and completion of grading, student submissions were de-identified by copying the text entries (without identifying information) into a spreadsheet. Each student name was replaced by a unique random number between one and twenty-eight using dice, and each student’s entire submission catalog was then copied into the spreadsheet under the appropriate column. (Thus, “Jane Smith” might become “Student 12”). This labelling allowed us to keep track of changes to student attitudes longitudinally within the semester without noting or publishing any identifying student information.

Prior to copying of student submissions from the online course-management system, details of the proposed study were submitted to the USF Institutional Review Board (IRB) for approval. Because the semester had concluded, the IRB approved a waiver of informed consent, provided that the students’ information was removed. The project was granted IRB approval e29371.
Analysis

Research Question.
Stipulated that this study was post hoc, the following research question drove the analysis of the existing data:

- How did students’ self-reported attitudes about math change after being assigned to read and respond to The Math Instinct (Devlin 2005)?

Coding.
Data were copied from the master spreadsheet to a word processing document, and responses were studied for common phrases and words (codes). Coding was performed using grounded theory – that is, codes were determined based on what appeared in the data, not predetermined codes (Glaser and Strauss 1967). All coding was done by VR. Four general codes were identified in the reading:

- Positive attitudes about mathematics.
- Negative attitudes about mathematics or math classes.
- Interest, fascination, or “liked reading” something from the assigned book.
- Thinking which began or changed due to something the student encountered in the book.

Results

Summary of the Assigned Book

The Math Instinct (Devlin 2005) makes the following statement on the back cover:

There are two kinds of math: the hard kind and the easy kind. The easy kind, practiced by ants, shrimp, Welsh corgis – and us – comes naturally. The hard kind… well, it doesn’t come naturally to many of us.

In The Math Instinct, Keith Devlin argues that, if we want to do better in formal math, we should see how it arises from natural mathematics – and he shows us how to get the most out of the skills we already have.

Chapters 1 through 8 concentrate on examples of what Devlin refers to as natural mathematics – that is, activities that require an understanding of patterns that can be expressed mathematically – such as a dog determining (correctly and repeatedly) the most efficient path to run and swim to chase a ball thrown into the ocean at an angle. Chapters 9 through 12 transition to a discussion of abstract mathematics – the sort of thing one generally learns in a mathematics classroom in school. Chapter 13 ends the book by discussing the way math is taught in school and giving some tips on how to optimize learning within that system. Table 1 includes a statement on each chapter from 13 selected students.
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Quotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>From reading chapter 1 of “The Math Instinct,” I learned that numerosity is sense of numbers, the most basic instinct developed at a very young age. I was surprised to learn that infants as young as 4 days old can recognize the difference between having more or less of something when it comes to small numbers (0, 1, 2, 3). – Student 15</td>
</tr>
<tr>
<td>2</td>
<td>Chapter 2 was interesting to me because he broke down calculus, and math in general, into its most fundamental parts. He said that Elvis, the welsh corgi, was performing calculus on the ball every time he ran along the beach and then into the water to retrieve the ball calculating the shortest possible distance. This made me think about our everyday lives and how we as humans are constantly calculating things without even realizing it, like driving a car and knowing when to pass a car driving the same speed as you, so you adjust your speed accordingly. – Student 17</td>
</tr>
<tr>
<td>3</td>
<td>This chapter has been the most interesting to me so far. The way this chapter explained what math is, is a way I knew existed but had never really had explained to me or had been one I had thought much about. I like the distinction one can make between &quot;math&quot; as it is normally thought of and &quot;Natural Math.&quot; In my opinion, if kids were taught math as a way of pattern recognition and rules of logic as opposed to rearranging of numbers, more people would have a better view and understanding of it. – Student 11</td>
</tr>
<tr>
<td>4</td>
<td>I am just as interested in the Tunisian ant finding the fastest way home as I am in the lobster's Magnetosphere like powers. The ant's ability to successfully navigate back to a hole a millimeter big is one amazing internal compass. Direction is one thing, but to know the exact distance is mind blowing. I knew something about lobsters migrating to the same area to reproduce but never thought about how they find their way. Sensing Earth's magnetic field would have never even been a thought. – Student 9</td>
</tr>
<tr>
<td>5</td>
<td>The honeybees innate ability to build perfect regular hexagons was astounding to me. Honeybees accuracy in making sure that all the widths are exactly the same and they all meet at 120 degrees far surpasses my ability, even if I had all sorts of tools available to use. Although the spider wasn't intentionally building a beautiful geometric shape, the end result is still impressive. This chapter left me wondering why we haven't evolved to be able to do mathematics to this degree with instinct. – Student 16</td>
</tr>
<tr>
<td>6</td>
<td>What I found most interesting is that leaves wind around the stem of a plant according to the Fibonacci sequence. I already knew that many types of flowers have a Fibonacci number as their number of petals from a documentary I had watched, but I didn’t know that trees followed the sequence as well with their leaves. It’s incredible that the leaves on a stem grow so as to maximize the amount of sunlight they receive but also make sure to not block or be blocked by other leaves. There is no way I’m going to be able to walk past a tree anymore without stopping to examine a branch to see if the leaves have a divergence that includes Fibonacci numbers. – Student 19</td>
</tr>
<tr>
<td>7</td>
<td>Reading through this chapter really made me think about what all goes into the aspect of motion of the everyday things we have around us. One example in the book that stood out to me the most was when the author was comparing how fish propel themselves by pushing the water sideways with their tale; birds fly by flapping their wings to create lift and forward thrusts. Both of these creatures are completely different, but manage to find a way to make motion work in their favor. Looking at how there are many different ways that represent different views of motion, gets your mind thinking when you realize all it comes down to is two physical principles which are mass and acceleration. – Student 4</td>
</tr>
<tr>
<td>8</td>
<td>What I found most interesting in chapter 8 was the two ways that the brain uses to determine depth. The first way being the measurement between the angle of the two eyes as they focus on a distant object. The second way being how much the eye distorts in order to bring an image into focus. It’s amazing how such a complex process is done nearly instantaneously in the brain without conscious thought. – Student 10</td>
</tr>
<tr>
<td>9</td>
<td>Devlin wraps up his exploration of animals performing mathematical feats in Chapter 9 with his classification of which animals actually perform math and which ones use their adaptations from natural selection. The difference between both categories is the manipulation of numbers and concepts via mental processes. While a lot of animals cannot perform mental math in the traditional sense, some can be trained to do mathematical concepts. The animals that are able to do this are: rats (although I found the training to be inhumane and saw their learning as one based on fear rather than curiosity), birds (with their number sense), lions (also number sense), and chimpanzees (with the ability to perform simple arithmetic). On a related side note, I found the Hans the Horse story to be incredibly humorous as the poor trainer wanted his horse to do math and the horse simply followed his trainer’s cues with no mental thoughts whatsoever. – Student 24</td>
</tr>
</tbody>
</table>
Chapter 10

Reading about "street mathematicians" in South America and how they use transformation rules to quickly solve their problems is another reason how practice and motivation is the only way to improve math skills. These children depend on math and therefore are highly motivated to get to the right answers as Keith Devlin explained. To something most students relate to these days is that math classes teach people how to perform on tests but they do not teach how to solve real life problems. This is problematic because if you're away from these methods for a period of time you not only forget how to do the problems on a test but you also end up having to teach yourself how to solve real life problems, as was the case for shoppers. If real life math skills such as the transformation rules were taught at a younger age in math classes, I think all of us would see more success in basic math on both tests and real world situations. I'm always surprised how quickly my father always beats me to the answers of arithmetic problems and now I'm curious whether that is something they taught him in school in (...) or just through real world experience. – Student 6

Chapter 11

This chapter is about counting and its various forms and meaning to people. The author spends a good portion of the chapter just discussing how humans are born with an innate ability to differentiate up to the number three. He also covers how counting has played a part of civilization in various forms from India to Arabic countries. It is heavily argued that counting has a different meaning to each person and in each case, can determine their ability to count. Some people numbers mean a great many things and are gifted counters while others are comfortable in the basic regard of counting. The chapter ties it together by stating that mathematics is a fantastic form containing many meanings but to each person, this meaning can define how they choose to see math, some will love wholeheartedly and others not so much. – Student 7

Chapter 12

Chapter 12 was quite interesting. This chapter helped me to understand why I tend to struggle with math and why I tend to forget things right after a test. I enjoyed reading about how people struggle with seemingly meaningless sequences of operations on insignificant symbols, and then as a result they end up with very odd-ball answers. I do this a lot, if I don't understand something I will make up my own equations or set of rules for a problem. And then as stated in this chapter once the correct answer is explained to me, it makes total sense. In addition, I really find it interesting that people are better able to do math if it pertains to real life. I never even thought of that. My favorite part about this chapter was when the author talked about school arithmetic and how people never get to the meaning stage; and it just remains forever an abstract game of formal symbols. I feel like this is truest statement about math. – Student 26

Chapter 13

This chapter is about how natural mathematics is a product of the mechanism of evolution. That we have been using the same innate mathematical processes since the Iron age. That the development of "abstract mathematics" is still a very new thing and is still very unfamiliar to many. The chapter also covered ways to improve one's mental math skills. – Student 21

Counts and Percentages

The writings of all 28 students were reviewed for this study. Three had a clear positive attitude about math at the beginning; two had a mostly positive attitude; four had a negative attitude, and the remaining 19 had a mixed positive/negative attitude at the start. Student 21 did not complete the first (initial-attitude) assignment; however, this student self-evaluated the initial attitude at the start of the final assignment and was counted as “mixed,” which appeared consistent with the student’s statements on chapter readings.

There were 15 separate assignments (the introduction, 13 chapter responses, and the final statement) for each of 28 students; therefore, there were 420 total assignments. The non-response rate was 13% (Fig. 2a). There were 13 chapters in the book, and 28 students reading the book; therefore, there were 364 chapter-response assignments. Out of that total, 51% of the individual chapter responses were coded as being “interesting” or “fascinating” in the students’ own words (Fig. 2b), and 26% were coded as including an explicit statement that the chapter
provoked a new or changed line of thought (Fig. 2c). It should be noted that this last code was also seen in a majority of the final assignment responses.

![Figure 2. Results.](image)

(a) Proportion of assignments turned in (green) (367/420);
(b) Proportion of chapter-response assignments that were said to be “interesting” or “fascinating” in the students’ own words (red) (185/364);
(c) Proportion of chapter-response assignments that included a statement that the reading provoked a new or changed line of thought (red) (94/364).

Student attitudes were assessed at the start and end of the reading and writing assignment. Attitude changes were examined and classed into three groups: improvement, minor improvement, and unchanged. (See Table 2.) No students exhibited any signs that their attitude toward math became more negative after reading the book, although not all students enjoyed the book itself. For the groups identified in the starting assignment:
• 3 Positive attitudes at start
  o 2 Improvement
  o 1 Minor Improvement
• 2 Mostly Positive attitude at start
  o 1 Minor Improvement
  o 1 Unchanged
• 19 Mixed attitude at start
  o 11 Improvement
  o 6 Minor Improvement
  o 2 Unchanged
• 4 Negative attitude at start
  o 4 Improvement

Table 2.
Student Starting Attitudes and Changes

<table>
<thead>
<tr>
<th>Student</th>
<th>Attitude at start</th>
<th>Attitude at end</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mixed</td>
<td>Minor improvement</td>
</tr>
<tr>
<td>2</td>
<td>Mixed</td>
<td>Improvement</td>
</tr>
<tr>
<td>3</td>
<td>Mixed</td>
<td>Improvement</td>
</tr>
<tr>
<td>4</td>
<td>Positive</td>
<td>Improvement</td>
</tr>
<tr>
<td>5</td>
<td>Positive</td>
<td>Improvement</td>
</tr>
<tr>
<td>6</td>
<td>Mixed</td>
<td>Improvement</td>
</tr>
<tr>
<td>7</td>
<td>Mixed</td>
<td>Improvement</td>
</tr>
<tr>
<td>8</td>
<td>Positive</td>
<td>Minor Improvement</td>
</tr>
<tr>
<td>9</td>
<td>Mostly positive</td>
<td>Unchanged</td>
</tr>
<tr>
<td>10</td>
<td>Mixed</td>
<td>Minor Improvement</td>
</tr>
<tr>
<td>11</td>
<td>Mixed</td>
<td>Unchanged</td>
</tr>
<tr>
<td>12</td>
<td>Mixed</td>
<td>Minor Improvement</td>
</tr>
<tr>
<td>13</td>
<td>Mixed</td>
<td>Minor Improvement</td>
</tr>
<tr>
<td>14</td>
<td>Negative</td>
<td>Improvement</td>
</tr>
<tr>
<td>15</td>
<td>Negative</td>
<td>Improvement</td>
</tr>
<tr>
<td>16</td>
<td>Negative</td>
<td>Improvement</td>
</tr>
<tr>
<td>17</td>
<td>Mixed</td>
<td>Improvement</td>
</tr>
<tr>
<td>18</td>
<td>Mixed</td>
<td>Minor Improvement</td>
</tr>
<tr>
<td>19</td>
<td>Mostly positive</td>
<td>Improvement</td>
</tr>
<tr>
<td>20</td>
<td>Mixed</td>
<td>Improvement</td>
</tr>
<tr>
<td>21</td>
<td>Mixed</td>
<td>Unchanged</td>
</tr>
<tr>
<td>22</td>
<td>Negative</td>
<td>Improvement</td>
</tr>
<tr>
<td>23</td>
<td>Mixed</td>
<td>Improvement</td>
</tr>
<tr>
<td>24</td>
<td>Mixed</td>
<td>Minor improvement</td>
</tr>
<tr>
<td>25</td>
<td>Mixed</td>
<td>Improvement</td>
</tr>
<tr>
<td>26</td>
<td>Mixed</td>
<td>Improvement</td>
</tr>
<tr>
<td>27</td>
<td>Mixed</td>
<td>Improvement</td>
</tr>
<tr>
<td>28</td>
<td>Mixed</td>
<td>Improvement</td>
</tr>
</tbody>
</table>

What the Students Said

Table 3 includes a selection of some student responses to give a flavor of the students’ reactions to the reading experience. They have been edited for grammar and spelling, but not content.
Table 3. 
Selected Quotations

<table>
<thead>
<tr>
<th>Student</th>
<th>Snippets</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>“I have had some bad experiences with math teachers and how they approach the subject.” “This book has changed my perspective for the better toward math taught in the class and has opened me to the possibility of taking my math education further in terms of calculus 3.”</td>
</tr>
<tr>
<td>11</td>
<td>“[Math] is an important tool in and out of the field of geology… I wish it was something that came more naturally to me.” “The book didn’t change my views on math much. It did change my view on how math should be taught in lower grade levels.”</td>
</tr>
<tr>
<td>15</td>
<td>“My first attempt at calculus 2 is the stuff of nightmares.” “Going back to basics to understand why we learn the way we do and how we think helps me to perform better.”</td>
</tr>
<tr>
<td>17</td>
<td>“I have learned that there are two different types of math, which I never considered before. There is abstract math, which is the math we learn in school and fail on calculus tests, and then there is natural math, which is the innate math skills we are born with.” “Both are just as important as the other, and this book helped me realize that mathematics is a blissful combination of both.”</td>
</tr>
<tr>
<td>18</td>
<td>“I always enjoyed math when the teacher was fun to listen to and explained the concepts in detail and didn’t rush through it because there was a deadline to meet by the end of the year for a test of some sort. During those years in which the teacher was seemingly “going through the paces” I did not enjoy the class and I also noticed that my grade would suffer as well because I would find myself bored and uninterested.” “Seeing how practically everything in the world is using math or math related shows just how important a subject that it is.”</td>
</tr>
<tr>
<td>19</td>
<td>“There is no way I’m going to be able to walk past a tree anymore without stopping to examine a branch to see if the leaves have a divergence that includes Fibonacci numbers.” “This book makes me want to become a math teacher. (…) I want math to have meaning for everyone.”</td>
</tr>
<tr>
<td>23</td>
<td>“Mathematics… has… been quite difficult for me. The problem is… a lack of understanding of why I was performing such calculations.” “Everything changed for me when I first took a course in statistics. The problems suddenly had meaning and real world applications.” “This book was the answer to so many questions I have had throughout my academic career beginning in the 9th grade.” “It truly changes the way you look at math problems and has actually helped me in other classes throughout this semester.”</td>
</tr>
<tr>
<td>24</td>
<td>“I only perceived math as a tedious and necessary requirement for a program.” “I do not think my perception of mathematics has changed significantly from reading this book as most of my personal success in the subject has been with effort and resolve. However, I better understand why abstract math is incredibly difficult to grasp and retain.”</td>
</tr>
<tr>
<td>27</td>
<td>“I still enjoy [math], and quite often wonder what other mathematics haven’t even been discovered yet that will revolutionize our way of thinking.” “[The Math Instinct] was very thought-provoking for me, and I have definitely learned something about myself in [reading and responding to it].”</td>
</tr>
<tr>
<td>28</td>
<td>“Most math classes, such as algebra and geometry, tend to just use math in a manner where the only outcome is just another number, without much reason to find that number other than it being a correct answer. Classes such as these, even though I have done well in them, take a lot more self-motivation and less enjoyment than those (chemistry) where using the math is part of the enjoyment. But that all changed once I reached the calculus level of mathematics. Calculus, to me, is a puzzle.” “Overall, what Keith Devlin’s The Math Instinct has allowed me to do is think about not just math, but everything in my surroundings in a different manner.”</td>
</tr>
</tbody>
</table>

Even in a small set of examples, comments coalesce around themes. For example, while the phrase “math anxiety” was not directly mentioned by any of the students, the phrase “test anxiety” was mentioned by Students 24 and 16 in reference to
chapter 10. Student 24 stated, “While confidence may play a factor in how well you perform when doing arithmetic, other factors, such as temperament, view towards mathematics, and test anxiety affect performance as well.” Meanwhile, Student 16 said,

If you ask someone a simple question in a casual conversation, they won’t feel the pressure to be right. Of course, in a casual conversation, you would also tend to estimate rather than doing a precise calculation. However, in a testing situation comes test anxiety. You tend to second guess yourself in test situations and overthink the problem. I think that a lot of people fail to master mathematics in school because of the way the problems are presented to them.

Then, in the final, summative assignment, Student 16 said,

The one critique of the book I have is in regards to chapter 10, which primarily focuses on “street mathematics.” Maybe it is because the researchers weren’t psychologists (or students recently), but it seemed painfully apparent to me why the vendors and shoppers didn’t do as well with the abstract math. Anxiety surrounding tests is extremely common. Though these vendors and shoppers weren’t under the pressure of these grades actually being recorded and potentially impacting their lives, I know that I still would have had test anxiety in their situation. Nobody wants to appear unintelligent, so on a test they will most likely second guess themselves and overthink the problem to try to get the best score possible. I talked about this chapter with a few classmates as well, and they were also surprised that Devlin didn’t really mention this factor.

Another common theme in the student responses was having a positive attitude or set of experiences regarding math until some pivotal experience changed them. Student 25 described a situation where the student did extremely well in mathematics courses in junior high and high school until taking an AP Calculus, which was taught by a new teacher, and “it was the worst experience I’ve ever had in a classroom.” This student did well in pre-calculus at USF, but struggled in calculus 1 (passing with a B), before failing calculus 2 more than once. Similar statements were noted from Students 2, 3, 6, 7, 10, 11, 13, 19, 20, 22, and 27.

Student 8 finished the assignment by saying, “I did not believe it when they [presumably LV and VR] said that this book is not like other math books, but now I do.” This sentiment was also relatively common through other student statements. Student 23, for example, said, “I dreaded cracking the pages of this paperback due to the preconception of boredom waiting in my future,” but Student 23 later came to say, “After reading all the chapters I found that this assignment was not menial or boring, it was actually enlightening and probably one of the best reads of my college career.” Several students mentioned having an intention to re-read the book

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3 Chapter 10 of *The Math Instinct* discusses street vendors in South America who are able to perform seemingly amazing feats of mental calculation as part of their daily lives, but who, when placed in a testing environment, have difficulty scoring well on math problems such as one would see in school.
later, with Student 27 saying, “it will be placed on my bookshelf to gather dust until I’m ready to read it again.”

Several students discussed whether the way students are educated in math should change. Student 13 said, “Maybe our education system should rethink its structure of standardized tests and abstract math to better prepare students for real world problems they will encounter.” Student 3 connected the way math is taught to why word problems are “dreaded.” Student 7 described liking math but having a “general dislike for how it was taught.” Student 10 actually expressed a desire to become a math teacher after reading the book to help change lives for the better.

Some students projected their positive experience with the book to the course itself. Student 16 said, “This book has changed my outlook on the subject, and the course has changed my experience with mathematics (for the better).” Student 25 said, “Having read The Math Instinct, I feel more open and confident when approaching math as a subject in school. The computational geology course has pushed me out of my comfort zone all semester in regards to mathematical concepts and solving word problems.”

**Discussion and Conclusion**

As noted in the literature, math anxiety – and for that matter, any other affective attitude about math – can come from experiences in school due to how math is presented (Norwood 1994). This connection was noted in several students’ comments about where, when, why, and how they stopped having a positive attitude about math. (Although none of the students used the words “math anxiety,” it seemed clear that that is what they were describing.) Several students in this study discussed having past negative experiences specifically with math courses. This finding is consistent with anecdotal data from past class cohorts and with interviews with alumni of the course (Ricchezza 2016).

To say that our assignment was successful in the pedagogical sense would be an understatement. Looking forward, an assignment such as this one is all but certain to be included in the fall 2017 semester syllabus (the book chosen and the details may change, but the essence of the assignment will not). The question for us is not whether we will include such an assignment, but merely what the details will be. One student, for example, would have preferred a choice of books to read rather than simply being told which one was required.

It would be dishonest to suggest that the notion of tackling the affective domain in math (or its subset, math anxiety) was on our minds when we assigned this work. When the reading and writing assignment was constructed and given to students, the major purpose behind it was to improve certain potentially deficient aspects of

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4 Actually suggestions are welcome. Please contact the first author.
their QL – that is, to make students more comfortable reading and writing about mathematics. So we also need to admit our good fortune in selecting *The Math Instinct* as the reading material for the semester book. The tone and style of the book reads like a National Public Radio story. In this regard it is worth noting that Keith Devlin is, indeed, “The Math Guy” on NPR’s *Weekend Edition*, and he is experienced at making his audience feel that, with a bit of explanation of what math is, and a good bit of practice, any of them could be math wizards.

The combination of the reading/writing assignment with the significant amount of contextualized mathematical practice that students get in the CG course appears in this case to have been at least somewhat successful at reducing math anxiety for the students involved. Taken more broadly, the emotional attitude the students showed after reading the book was improved for most students. While the post hoc nature of the study, the single course term/cohort, and the limited nature of the study prevent us from generalizing this study to any broader population, we strongly believe – and we know we are not alone in our belief – that QL-in-discipline courses are an important method for improving student success in QL (Madison 2001), and we think that assignments such as the one we used may be helpful to instructors and students of such courses.

If a formal follow-up study were to be conducted, such a study would include:

- Informed consent (all students would complete the assignment for class credit, but student work would not be used in the study without permission).
- Questions and writing prompts altered to specifically encourage discussion of emotional reactions to math instruction and the assigned text.
- A follow-up survey (not counted for class credit), most likely mixed-methods (quantitative and qualitative), giving students an opportunity to discuss responses openly, anonymously, and without fear of reprisal. (This should also mitigate to some degree the confirmation bias of students telling us what they think we want to hear).
- A determination – to quote an anonymous reviewer – “whether any ‘popular mathematics exposition book’ would yield similar results.” (Note: this question could easily lead to a different paper entirely.)

We encourage any readers so inclined to consider further studies of affect change brought about by side reading of mathematical popular nonfiction while taking a hard-core math – or contextualized math – class, as questions raised by our observation in CG merit exploration.

**Limitations**

As with any primarily qualitative study, this one has limitations. The assignment set was not designed for a study, but to improve students’ abilities to read and write about math concepts. Were a study to be designed from scratch, it would certainly be done differently.

All statements are based on the students’ own words. Not only must we take them at their word, we must assume they are being fully expressive, despite
minimal prompting. That is to say that one student saying 8 of 13 chapters were “interesting” may simply be that student’s style of writing, while another student not saying so explicitly is assumed here to mean that that student did not find the book interesting (when this may not be true). A study designed to elicit attitudes about math or a book response would need to be more explicit in asking respondents about items, whether through a survey or through interviews. It should also be noted that in interviews, follow-up questions can be asked; in this case, we are reviewing educational records and cannot ask students for clarification. We must also acknowledge the possibility of confirmation bias in students submitting what they think we want them to say.

Many of the codes and classifications are somewhat arbitrary in the sense that what one person might consider a mixed attitude, another may consider mostly positive. Likewise, not every person clearly stated a change in attitude at the end of the readings/course, and this code had to be inferred from what they said. Making such a determination from a records review rather than surveys or interviews introduces an additional level of uncertainty.

This post hoc study is not intended to be generalizable to any broad population.

Acknowledgment

We wish to thank the three thoughtful reviewers who helped refine this note for publication. We’d also like to thank the 28 students in the fall cohort of CG, without whose excellent writing responses this note would not have been considered.

References


Have you ever tried presenting graphs to your students only to experience frustration when they look first to the data points, ignoring important information on the graphical axes? Does this frustration lead to a less quantitative presentation of your course—do you leave the graphs (or the math behind them) out entirely? Geoscience courses are often viewed as being qualitative, despite the fact that modern geoscientists practice in a thoroughly quantitative field (Manduca et al., 2008). Enhancing our students' skills and experience in quantitative reasoning in undergraduate geology courses can be difficult, but it is essential if students are to work successfully in the profession after graduation (Manduca et al., 2008; Vacher, 2012). Geoscience courses offer a precious opportunity to present mathematics in context (Wenner et al., 2009), which we cannot let pass us by. Two topics that fit very nicely together, and are quite relevant to geosciences, are logarithmic scales and graphing modeling functions. In this article we discuss a unit from our course, and how it teaches these concepts.

In addition to mathematics courses, geology students at the University of South Florida (USF) are required to take a course to improve application of quantitative skills to geoscience. One popular option is a course in Computational Geology (GLY 4866, hereafter CG). The CG course covers a variety of mathematics topics in geologic context, with integrated problem sets, worked examples, and lab activities (Ricchezza, 2016; Ricchezza and Vacher, 2016, 2017; Vacher, 2000b).

The CG course uses problem sets to improve quantitative skills. The problem
sets include homework packets with worked examples of the week's new topic(s) and multiple problems to be worked through by the start of the next week's class. One sample problem, given the first week of class, says "My office is on the fifth floor of SCA. There are two flights of stairs between floors, and 12 steps per flight. When you walk up the stairs to my office from the parking lot, how many stairs do you climb?" (Answer at end of article.) Students complete ten of these weekly sets, then take a quiz on the material (to encourage completion of the problem sets). In the second of the two class sessions each week, students meet with the graduate teaching assistant (TA) for a lab, during which they perform practical operations related to the week's problem set (Fig. 1).

Among the CG topics of interest to a wide (interdisciplinary) geoscience audience is logarithmic scales, including their relationship to modeling functions. We have found that a fundamental weakness our students have in the general area of quantitative literacy (QL) is the ability to "see" and grasp deeply information communicated in a graph. It is through teaching logarithmic scales and modeling functions that we hope to address this common deficiency (Vacher, 1998a, b, 1999, 2000a, 2003, 2004, 2005). (See http://nagt.org/nagt/jge/columns/compgeo.html for additional columns related to this course.)

Problem Set 8 (of 10) is Logarithms and Log Scales (see Fig. 2), an essential topic for seismology and geochemistry (among a variety of other areas of practice in and out of the geosciences). The lab for this problem set/topic is "Slide Rules and Log Scales." For those born a bit too recently to have experienced their use the first time around, logarithmic slide rules were used for centuries as a calculation aid and were essential to such science and engineering tasks as putting humans on the Moon and returning them safely to Earth. Slide rules make use of the properties of logarithmic scales and the rules for their interactions to assist the user in performing calculations (for a brief history of slide rules, a tutorial on their usage, and a virtual slide rule application, see http://sliderulemuseum.com/SR_Course.htm ). To complete this lab, students are provided with logarithmic slide rules that were produced on 3D printers (the 3D-printed slide ruler template can be accessed free at http://www.thingiverse.com/thing:2305300) at the USF Alliance for Integrated Spatial Technologies (AIST), with labels from a paper–based slide rule printed on
Reasoning in the Geoscience Classroom: Modeling Functions and Logarithmic Scales

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blank labels rather than standard paper and applied to the plastic sliders (our slide rules were labeled with a paper slide rule model developed by Scientific American [https://www.scientificamerican.com/media/pdf/Slide_rule.pdf](https://www.scientificamerican.com/media/pdf/Slide_rule.pdf)). Students complete 2–4 calculation problems using the slide rule for each type of calculation available (multiplication, division, squaring, square root, cubing, cube root, reciprocal, sine, tangent, and common logarithm), with some calculation problems chosen to require additional thought. That is, logs on the slide rule can be done only for base 10 (common logs), so students were given a log in a different base; likewise, logs on the slide rule can be done only for numbers up to 10, so students were given values above 10 to require use of rules of manipulating logarithms in order to complete the problem. Additional issues arise in the placement of decimal points and the location of zeroes, as log scales on a slide rule generally run from "1" to "1", and we require the students to understand why. Students learn through this experience that the slide rule was (and still is!) a useful tool, but that it did not and does not think for them. Figure 3 shows the 3D-printed slide rule.

The final portion of the Slide Rules and Log Scales lab is completed by students being handed two sheets of standard graph paper and being tasked with constructing two log scales and using these scales to construct a standard multiplication/division slide rule. Successful students are able to complete the final portion of the assignment properly if they understand how log scales work and how they relate to arithmetic scales (such as those on standard graph paper).

Returning to the learning goal, a novice learner will often find the eyes drawn to the data points (or curves) on a plot. In contrast, a more experienced learner, such as, we hope, a veteran of this course, will look first at the axes of the graph. Figures 4a and 4b show an example of why the 'eyes-to-data' view is problematic and the 'eyes-to-axes' view is helpful. The seismic energy, plotted versus the earthquake magnitude, produces two very different-looking plots, depending whether one uses standard arithmetic graph axes or semilog paper (that is, one arithmetic axis and one logarithmic). Additionally, the "standard" plot (see Fig. 4a) shows little to no visible difference between most of the data points until magnitudes 8 and 9 are reached – in fact all of the energy values for magnitudes 7 and below appear to be zero, which is not true – correct determination of the energy readings from this graph is nearly impossible. Finding the energy reading on the semilog plot is simple... provided the learner knows how to read a logarithmic scale (see Fig 4b). [Note: this particular pair of
graphical plots deals with energy released through seismic waves from earthquakes. For those unfamiliar, earthquakes release energy when sudden movement occurs inside the Earth, and this energy travels as seismic waves. For more information on earthquakes, see United States Geologic Survey resources at https://earthquake.usgs.gov/learn/ and https://pubs.usgs.gov/gip/earthq1/.

This learning experience is followed two weeks later by the final problem set and lab (see Fig. 5), focused on four standard modeling functions (linear, logarithmic, exponential, and power functions). As with the prior problem sets, students complete the set on their own, take a quiz, have the instructor work through the quiz and fundamentals of the set, and review worked versions of the set and quiz. Students then meet for the final lab where they graph modeling functions. In this lab, students are given two ordered pairs of \((x,y)\) coordinates. They are then given two \(x\)-values, with one falling between the two given points, and one outside. Students are provided with four sheets of different graph paper: standard (arithmetic) graph paper, semi-log paper (with log scale on the \(x\)-axis), semi-log paper (with log scale on the \(y\)-axis), and log-log paper. They are then asked to plot the two ordered pairs on each different set of graph paper, draw an apparent straight line through those points, work out the equation of the "line" (i.e., the function), and find the two missing \(y\)-values. Based on their experience during the problem set and the prior class session, the students should know that these four sets of graph paper, if they appear to show a straight line, actually represent linear, logarithmic, exponential, and power functions, respectively, and, moreover, that they have been provided with the necessary information to find all that has been requested of them in the lab.

What's the point of all this?
As noted earlier, when students enter our course, they make the mistake many students (and indeed many university graduates) make when reading a graph: the first thing they look at,
aside from perhaps a title, is the cloud of points or trendline in the data. By the conclusion of the CG course, our hope is that students first look is at the axes of the graph, so that by the time they look at the actual data they have already preset their minds to analyze the sort of functions and data sets that might be framed by variations in the axis scales and labels. A USF geoscience alumnus who took this course wouldn't see just a series of points arranged in a straight line – they'd (for example) see a logarithmic scale on the y-axis and an arithmetic scale on the x-axis and rightly judge that "straight line" to mean an exponential function (see Figure 4b). While this specific goal won't be the same for all geoscience courses, and certainly not for all educational levels, the goal of quantitative literacy is something reasonable and attainable for the courses on which we all work, and we hope this set of activities from our course gives you some ideas you can use to make your courses more quantitative.

**Answers to sample problems:**

*Problem 1:* Note that in the building (SCA), the ground floor is actually floor 1, so the correct answer is 4 intervals x 2 flights/interval x 12 steps/interval = 96. Many students will incorrectly place the number of intervals at 5, failing to account for the starting number of 1.

*Figure 2:* a. 12 yard line. b. 90 yard line

*Figure 5:* a. this is an exponential function where E rises 3 log cycles for every 2 levels of M. b. Joules: log = 1.5 + 4.8.; tons TNT: log_{ton} = 1.5 - 4.8. c. value of E at magnitude 0 is 6.3 x 10^4 joules, and increases to 31.6 times as much for each step. Value of E at magnitude 0 is 1.6 x 10^{-5} tons of TNT and increases by the same multiple. d. Magnitude 7.2

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Comment? Start the discussion about ONLINE EXTRA: Quantitative Reasoning in
Research on Cognitive Domain in Geoscience Learning: Quantitative Reasoning, Problem Solving, and Use of Models

Kim Kastens, Lamont-Doherty Earth Observatory; Ashlee Dere, University of Nebraska at Omaha; Deana Pennington, The University of Texas at El Paso; and Vic Ricchezza, University of South Florida


Introduction

Human cognition is the process of acquiring knowledge and understanding through thought, experience and the senses. Cognitive processes are habits of the mind and therefore affect learning, including the learning of geoscience concepts and skills. The GER Framework includes two chapters on areas of cognitive research that are particularly important to geoscience education: the previous chapter tackled spatial and temporal reasoning, and this chapter addresses quantitative reasoning, problem-finding and problem-solving, and the use of models.

Models (from simple mental models to complex computational models) are used by geoscientists to conceptualize and better understand the Earth system and to make predictions (Figure 1). Earth processes affect the human condition and result in hazards and complex issues that require both expert and citizenry decision-making about mitigation and adaptation. In addition, a wide range of Earth materials (e.g., mineral, rock, water) are valued resources that need sustainable management. All of these challenges require recognition of the problem (problem-finding), and the development and application of problem-solving skills. In addition, Earth system understanding and problem-solving benefit strongly from quantitative reasoning. Quantitative reasoning, problem-solving, and use of models present many daunting challenges to both students and instructors. All are valued by the professional geoscience community and by employers, and all would benefit from more education research.

Figure 1. Computational models, such as the STELLA Daisyworld model shown in this diagram, aim to help geoscientists figure out and describe how the world works. Components are identified and linked to explore quantitative relationships of cause and effect and feedbacks, evaluate system behavior, and make predictions. Effective teaching with models benefits from cognitive research on the use of models. Figure created by Dana Chayes.
In defining the Grand Challenges and recommended strategies, we favored those that are: high impact, under-researched, addressable on a ten-year time scale, and/or central to how geoscientists think about the Earth and about Earth/human interactions. Addressing each of these challenges will require innovative, creative thinking, along research pathways that are not yet clear, along with vast amounts of hard work. But we are confident that each of them is ripe for new discoveries, and we look forward to both the intellectual and practical outcomes of these efforts.

**Grand Challenges**

**Grand Challenge 1: Quantitative Thinking:** How does quantitative thinking help geoscientists and citizens better understand the Earth, and how can geoscience education move students toward these competencies?

The ability to think quantitatively is an important part of what transforms an introductory student into a geoscience major and then into a professional geoscientist. Employers value quantitative thinking. Quantitative thinking may be a sweet spot for GER research, in that there is rich trove of math education research to build upon.

**Grand Challenge 2: Problem-finding and Problem-solving:** How can we help students find and solve problems they care about concerning the Earth, in an information-rich society (e.g., of big data, emerging technologies, access to a wide-variety of tools, and rich multimedia)?

Historically the problems that students tackle in science classes, including geoscience classes, have been assigned by the teacher and rather constrained in scope. But many of the problems geoscience students will confront in the future are complex, messy, ill-defined, and require working across disparate knowledge, methods, and data sources.

**Grand Challenge 3: Use of Models:** How can we help students understand the process by which geoscientists create and validate physical, computational, mental, systems, and feedback models and use those models to generate new knowledge about the Earth?

Geoscientists use an ambitious and iterative process of building models, starting with mental working models and working up to computational models, testing their models against empirical data at every iteration. Only after many such cycles is the model considered robust enough to make predictions about the earth where we have no data—including the past or the future. Lack of understanding of how modern scientific modeling works allows skeptics and deniers to dismiss evidence that comes from modeling, for example evidence that climate change is anthropogenic.
Grand Challenge 1: 
How does quantitative thinking help geoscientists and citizens better understand the Earth, and how can geoscience education move students toward these competencies?

Rationale
The ability to think quantitatively is an important part of what transforms an introductory student into a geoscience major and then into a professional geoscientist. Employers value quantitative thinking. Quantitative thinking may be a sweet spot for GER research, in that there is rich trove of math education research to build upon. The set of recommended strategies listed below is not meant to comprehensively cover the entirety of geoscience quantitative thinking; we have prioritized strategies that we think offer the highest leverage and that will produce a strong foundation upon which future efforts can build.

The literature in quantitative reasoning outside of geoscience is extremely rich, including contributions in mathematics, mathematics education, statistic education, engineering education, computer science education, and educational psychology. Good starting points include Ashcraft (2002), Madison (2014), & Wing (2006). Several sources have indicated that modest gains in student attitudes can be achieved with some effort (Wismath & Worrell 2015; Lipka & Hess 2016; Follett et al., 2017; Ricchezza & Vacher, 2017). However, results are mixed and not all interventions have produced desired results (Sundre et al. 2012; Mayfield & Dunham 2015). Research on quantitative reasoning specifically within geoscience education is a fertile field for future work (Vacher, 2012; Ricchezza & Vacher, 2017).

Recommended Research Strategies

1. Collaborate with mathematics education researchers and quantitative literacy experts. There is already a large community outside of the geosciences who has thought about issues of quantitative thinking, and we want to be able to build on their efforts rather than start from scratch. Two anticipated research process outcomes from such collaborations would be gains in: (a) vocabulary and constructs with which to talk about how experts and novice participants in our studies are thinking and learning and (b) insights about mathematical habits of mind and partnering to better understand how these habits of mind come into play in thinking about the Earth. The following are example contact points to initiate collaborative research with mathematics education researchers and quantitative literacy experts.

   - National Numeracy Network
   - Research in Undergraduate Mathematics Education
   - Transforming Post-secondary Education in Mathematics
   - EDC Math Education group: Authors of Cuomo, Goldenberg, & Mark, 1996

2. Research how novices and experts take an Earth phenomenon that they understand holistically or experientially and transform it into a mathematical representation (e.g., word equation, mathematical equation, mathematical or computational model; Figure 2). Personal experiences as educators tell us that this is a skill that many students lack, and it is generally not being taught in math
classes. For geoscience majors, this is an essential skill for doing original research. For non-majors, this is a valuable life skill. There is very little research on this, and also not much guidance for educators. Models include the work of W.-M. Roth (e.g., Roth & Bowen, 1994) and the 1990’s vintage Jasper Woodbury series (Vanderbilt, 1992).

3. Research what quantitative habits of mind expert geoscientists use in understanding the Earth. Research suggests that habits of mind are more enduring and transferable than specific skills. We do not know what the geoscience careers of the future will entail, or what specific skills might be needed. Habits of mind should prepare students for whatever specific tasks are required. We and our math colleagues have put a lot of effort into teaching math skills; we now want to move beyond teaching quantitative skills to teaching quantitative habits of mind. This topic is seriously under-researched.

4. Work towards a community consensus on what quantitative skills and habits of mind are needed to function effectively as a citizen of the planet. Many of the critical Earth-related problems facing humanity can be broadly understood at either a qualitative or quantitative level; for example climate change, resource depletion, and resilience in the face of natural disasters. However, to move beyond merely understanding the problems, so as to be able to weigh the costs and benefits of conflicting paths forward, requires quantitative thinking. There is not a consensus on what the elements of such thinking should be, but the traditional algebra-calculus sequence seems not to be an optimal match. Deciding what needs to be learned is a necessary pre-cursor to designing a comprehensive research program in this area. This could be approached as a community discussion. Or it could be approached as a research question, looking out in the world at what kinds of tasks and decisions citizens face in the context of Earth/human interactions, and what quantitative capacities are needed to succeed at these tasks and make wise decisions.

5. Research what learning experiences can help students with poor math preparation or attitudes feel the power of math to answer questions or solve problems they care about concerning the Earth. Extensive literature in and out of the geosciences and uncounted personal experiences as educators tell us that many of our students enter our classes or our major(s) with a negative attitude about math (e.g., math anxiety, math phobia) combined with a lack of proper math preparation, that leads to math avoidance (Wenner & Baer, 2015; Maloney & Beilock, 2012). This shuts them off to the rich possibilities of the power of math to solve problems and open entire career opportunities they had not considered before. Improving quantitative thinking about the Earth is important for all students, but we prioritize this population for research attention because the problems here are so gigantic and so important, and because we think that this can be a pathway to transform math from “something I hate” into “something I want and need.”
6. Collaborate with assessment experts to develop and validate assessments for the learning goals articulated in Strategies 2 and 5, and to begin to shape the findings of Strategies 3 and 4 into assessable constructs. There are few to no tested, validated, research-grade assessment instruments that tackle quantitative reasoning in the context of Earth education. The building of such assessments requires both deep knowledge of the Earth and serious expertise in assessment; collaboration will be helpful. It might be possible to: (a) build Earth content into existing quantitative reasoning assessments, or (b) increase the quantitative component of existing Earth literacy assessments, or (c) formalize and validate assessments that have been developed as summative or formative assessments for coursework. Any of these pathways would need to begin with a clear articulation of learning goals and of what student behavior and/or product would demonstrate that each learning goal had been met. This is a long path; all the more reason to start sooner rather than later.
Grand Challenge 2: Problem-finding and Problem-solving: How can we help students find and solve problems they care about concerning the Earth, in an information-rich society (big data, emerging technologies, access to a wide-variety of tools, rich multimedia)?

Rationale
Historically the problems that students tackle in science classes, including geoscience classes, have been assigned by the teacher and rather constrained in scope. But many of the problems geoscience students will confront in the future are complex, messy, ill-defined, and require working across disparate knowledge, methods, and data sources. Such work has been coined “convergent” science, as solutions for problems must be converged on from different directions. We are at a time where technology can leverage the power of undergraduates so that they can make real contributions to solving authentic, messy problems, rather than being constrained to well-bounded classroom problems. Information technology has changed, and will continue to change, the kinds and quantities of resources that are available for problem solving. Students need to learn to navigate this rapidly changing space, identifying and harnessing resources (e.g. tools, data, models, experts, collaborators) that can be brought to bear on their problem. We anticipate that young people who learn to identify and solve convergent science problems as students will carry that skill-set and habit of mind into their personal, civic and professional adult lives (Figure 3).

The current state of knowledge on problem-finding and problem-solving comes from many fields of study that can inform future geoscience education research:

- There is existing research on the process of diffusions of innovation and on technology adoption (Rogers, 2003). Both of these identify awareness, perceived usefulness, and initial training as key early phases in the process of technology adoption. However, there is little research on how to enable these early phases in the sciences in general and the geosciences in specific.
- There is existing research on computational thinking and data analysis skills, mostly within computer science education (Elliot et al., 2016; Fox & Hendler, 2014; Hey, Tansley, & Tolle, 2009). Yet, there is very little research on this topic in geoscience, beyond identification of general categories of skills needed (Nativi et al., 2015). The Geoscience Employer’s Workshop Document identifies a set of existing technologies with which students need to be familiar; this list will change continually in the future but general types of technologies (e.g., GIS as opposed to the more specific software ArcGIS) may be an appropriate anchoring for tailoring research foci.
- There is a body of literature on problem-based learning, including in medicine, business,
engineering, and to a lesser extent in geosciences (Holder, Scherer, & Herbert, 2017; Pennington et al., 2016). Much of this literature comprises “curriculum & instruction” style papers rather than discipline-based educational research. Given the messy and heterogeneous nature of problems and problem-solving, it is hard for researchers to produce generalizable knowledge on problem-based learning, findings that can be extended beyond the immediate context of a study site.

- There is a body of literature on the science of team science and cognition in groups (National Research Council, 2015; Pennington, 2016; Pennington et al., 2013). This has mostly been developed through case studies of teams in different contexts – mostly within large organizations, medical teams, and community organizations. There is some emerging research on how learning occurs in teams (Borrego & Cutler, 2010; Bosque-Pérez et al., 2016; Roschelle & Teasley, 1995), and how activities can be designed in geoscience classrooms to develop these capabilities (Pennington et al., 2016).

**Recommended Research Strategies**

1. Research the problem-finding process; the techniques by which vague, open-ended problems are turned into solvable problems, and how these can be taught. Problem identification in convergent science requires the ability to co-create a shared conceptualization of the problem to be solved based on what each participant can contribute. There are an infinite number of ways to frame research on ill-defined problems; solutions depend on the expertise at hand. The challenge is to learn enough about the different contributing perspectives to determine how they can be collectively leveraged. Moreover, to make serious headway on a substantial problem, the problem and proposed solution has to be one that is of high importance to the solver or solving team; otherwise, they won’t have the motivation to push onward through the inevitable challenges and setbacks. Finding a problem that is both solvable and of passionate personal interest is doubly hard. We need evidence on how skilled problem-solvers do this, models for how learning occurs in these situations, and pedagogical approaches to help students learn to do the same. Employers, including those involved in the Future of Geoscience Education Employers Workshop, articulate the importance of learning to work on problems with no clear answers and manage the uncertainty associated with solving these types of problems.

2. Research the process by which geoscience students learn and adopt new methods and technologies. As technology advances, new tools are available that generate ever larger datasets. Such datasets are potentially valuable to help solve complex problems, but the most effective strategies for learning how to manage and extract solutions from large datasets are not clear. Skills are needed to: (a) skillfully collect, integrate and analyze data that are increasingly generated automatically by advanced sensors and/or simulation models; (b) understand advanced methods and technologies for conducting data-intensive science; and (c) timely identify and learn technologies that are relevant to the problem and are emerging at an increasingly rapid pace. Likewise, new technologies could be used to process data in new ways or to advance learning, but more research is needed on how to most effectively use such technologies, especially when technological developments constantly evolve. In addition, employers, including those involved in the Future of Geoscience Education Employers Workshop, articulate the importance of the ability to use data to solve problems.
3. Collaborate with experts on team science (from cognitive or learning science) to research effective strategies to teach collaboration and teamwork in undergraduate geoscience education. Convergent science requires the ability to collaborate effectively across disciplines and/or with external stakeholders, especially with experts from social sciences, engineering, and computer science. Employers, including those involved in the Future of Geoscience Education Employers Workshop, consistently emphasize the importance of ability to work in teams, including interdisciplinary teams. Although many classes incorporate team projects, most provide little training to students on how to work effectively in a team. There are few relevant models of teamwork training for geoscience faculty to follow, and most do not have the knowledge and expertise to construct their own models. Although there exists decades of research on teamwork in other contexts, there is little GER research on how what is known about teamwork can be applied in geoscience contexts.
Grand Challenge 3:  
Use of Models: How can we help students understand the process by which geoscientists create and validate physical, computational, mental, systems, and feedback models and use those models to generate new knowledge about the Earth?

Rationale
We have prioritized this Grand Challenge because we think that many or most citizens do not understand how modern scientific models are developed and tested, and how they are used to make predictions. Geoscientists use an ambitious and iterative process of building models, starting with mental working models and working up to computational models, testing their models against empirical data at every iteration. Only after many such cycles is the model considered robust enough to make predictions about the Earth where we have no data - including times in the past and the future. Lack of understanding of how modern scientific modeling works allows skeptics and deniers to dismiss evidence that comes from modeling, for example evidence that climate change is anthropogenic.

There is some good literature on how scientists create and validate models, including external runnable models (e.g. Nersessian, 1999), and including in geosciences (e.g. Weart, 2011; Turcotte, 2006). There is active research on how students and teachers understand the scientific practice of modeling (Clement, 2000; Gilbert & Justi, 2016; Gobert & Buckley, 2000; Grosslight et al., 1991; Justi & Gilbert, 2002; Lehrer & Schauble, 2006; Pluta, Chinn, & Duncan, 2011) and on scientists’ normative, conceptual models (Schwarz & White, 2005; Schwarz & Gwekwerere, 2007; Schwarz et al., 2009). There is less understanding of how students and teachers understand external runnable models, including physical models (Miller & Kastens, 2018), and modern computational models (such as global climate models) (Bice, 2006; Colella, 2000).

There are frameworks for model-based instruction, ready for testing (e.g. Sell et al., 2006; Sibley, 2009; Wndschetl, Thomson, & Braaten, 2008; Gilbert & Ireton, 2003), but a lack of good assessments of students’ ability to create and use geoscience computational models (Figure 1). There is a particular shortage of educational research at the interface between models and data: how to help students learn to use data to test models, and how to help students learn to use models to interpret data. As pointed out in an earlier theme chapter, we need further research on how to help students find the sweet spot between being overly skeptical about models and being overly trusting of models. Model-building as a collaborative process (Pennington et al, 2016) may be part of the process of creating trusted models around difficult problems.

Recommended Research Strategies

1. Research what students at various levels understand the process by which geoscientists create and validate models (especially modern computational models) and use those models to generate new knowledge about the Earth. It has been asserted (e.g. Kastens et al., 2013) that students and the general public have little understanding of the process by which the computational models of modern science are created, validated, and used to make predictions. The breadth, depth, distribution and nature of this ignorance needs to be probed, to lay the groundwork for a comprehensive research agenda.
2. Collaborate with cognitive/learning scientists to understand how the human mind runs mental models of the future and/or the past, and then use this understanding to research how geoscience education can improve and leverage that ability. The first step towards generating a scientific computational model of a part of the Earth system is to develop a conceptual model that can be “run” in the mind (i.e. one can envision processes that produce observable products or behaviors, and can think through how those products or behaviors would differ as circumstances or inputs change.) The ability to run mental models is thought to be unique to the human brain and is therefore a powerful cognitive tool we have to understand the world around us. Even without formal training, our brains have this inherent ability (for example, anticipating where one will and will not be able to find parking on campus), but it is unclear how this ability is applied to understanding earth systems and how we can leverage this power of the mind to inform education practices.

3. Research how the human mind understands positive and negative feedback loops, how geoscience education can foster that ability, and how can we assess this. The Geoscience Employers’ Workshop Outcomes lists the ability for students to do “systems thinking” as a valuable habit of mind. Cognitive research on ALL of systems thinking is beyond the scope of what could be accomplished in the 10 year timeframe to meet the GER Framework Goal); therefore we prioritize one critical aspect of system thinking for near-term cognitive research: feedback loops. Many, and maybe even most, environmental problems are underlain by reinforcing (aka positive) feedback loops; for example, the albedo feedback loop that strengthens the impact of climate change in the Arctic as the polar sea ice melts. Many of the potential solutions to environmental problems work by strengthening balancing (aka negative) feedback loops, or by weakening positive feedback loops. To understand environmental problems or contribute to environmental solutions in a deep and impactful way, students need to understand such processes. Practitioners find that these topics can be taught, but are challenging to teach and to assess. Feedback systems can be taught at a qualitative level or a quantitative level, and both are challenging. Understanding the cognitive underpinning of teaching and learning about feedback loops is a challenge that could benefit from collaboration with other DBER’s, perhaps through the DBER-A alliance, as feedback loops are very important in life sciences (ecology, physiology) and engineering.

References


**Figures**

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Figure 1.  
**Provenance:** Kim Kastens, Columbia University in the City of New York. Figure was created by Dana Chayes.

Figure 2:  
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Figure 3:  
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Victor,

Yes, you have my permission to use the graphics with proper credit.

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APPENDIX C: IRB APPROVAL DOCUMENTATION
8/14/2018

Victor Ricchezza  
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NES 107  
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RE: Exempt Certification  
IRB#: Pro00035492  
Title: The Geoscientist Quantitative Preparation Survey

Dear Dr. Ricchezza:

On 8/14/2018, the Institutional Review Board (IRB) determined that your research meets criteria for exemption from the federal regulations as outlined by 45CFR46.101(b):

(2) Research involving the use of educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures or observation of public behavior, unless:
(i) information obtained is recorded in such a manner that human subjects can be identified, directly or through identifiers linked to the subjects; and (ii) any disclosure of the human subjects' responses outside the research could reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, or reputation.

As the principal investigator for this study, it is your responsibility to ensure that this research is conducted as outlined in your application and consistent with the ethical principles outlined in the Belmont Report and with USF HRPP policies and procedures.

Please note, as per USF HRPP Policy, once the Exempt determination is made, the application is closed in ARC. Any proposed or anticipated changes to the study design that was previously declared exempt from IRB review must be submitted to the IRB as a new study prior to initiation of the change. However, administrative changes, including changes in research personnel, do not warrant an amendment or new application.

Given the determination of exemption, this application is being closed in ARC. This does not limit your ability to conduct your research project.

We appreciate your dedication to the ethical conduct of human subject research at the University
of South Florida and your continued commitment to human research protections. If you have any questions regarding this matter, please call 813-974-5638.

Sincerely,

Kristen Salomon, Ph.D., Chairperson
USF Institutional Review Board
Informed Consent to Participate in Research
Information to Consider Before Taking Part in this Research Study

Pro # 00035492

Researchers at the University of South Florida (USF) study many topics. To do this, we need the help of people who agree to take part in a research study. This form tells you about this research study. We are asking you to take part in a research study that is called: The Geoscientist Quantitative Preparation Survey. The person who is in charge of this research study is Victor J. Ricchezza. This person is called the Principal Investigator.

Purpose of the Study
This study is to determine how well prepared early career geoscientists feel regarding quantitative skills.

Why are you being asked to take part?
We are asking you to take part in this research study because we have reason to believe you may fall within the target population (persons with a bachelor’s degree in geology or a related field and 3-7 years of experience).

Study Procedures
If you take part in this study, you will be asked to go to a website and complete an anonymous survey. Your name and other identifying information will not be recorded.

Alternatives / Voluntary Participation / Withdrawal
You have the alternative to choose not to participate in this research study.

You should only take part in this study if you want to volunteer; you are free to participate in this research or withdraw at any time. There will be no penalty or loss of benefits you are entitled to receive if you stop taking part in this study.

Benefits and Risks
You will receive no benefit from this study. This research is considered to be minimal risk.

Compensation
We will not pay you for the time you volunteer while being in this study.
Privacy and Confidentiality

We must keep your study records as confidential as possible. It is possible, although unlikely, that unauthorized individuals could gain access to your responses because you are responding online.

Certain people may need to see your study records. By law, anyone who looks at your records must keep them completely confidential. The only people who will be allowed to see these records are:

- The Principal Investigator (Victor J. Ricchezza)
- The co-principal investigators (the PI’s faculty advisors, Dr. H.L. Vacher and Dr. Jeffrey G. Ryan)
- The University of South Florida Institutional Review Board (IRB).

It is possible, although unlikely, that unauthorized individuals could gain access to your responses. Confidentiality will be maintained to the degree permitted by the technology used. No guarantees can be made regarding the interception of data sent via the Internet. However, your participation in this online survey involves risks similar to a person’s everyday use of the Internet. If you complete and submit an anonymous survey and later request your data be withdrawn, this may or may not be possible as the researcher may be unable to extract anonymous data from the database.

Contact Information

If you have any questions about your rights as a research participant, please contact the USF IRB at (813) 974-5638 or contact by email at RSCH-IRB@usf.edu. If you have questions regarding the research, please contact the Principal Investigator at ricchezza@mail.usf.edu.

We may publish what we learn from this study. If we do, we will not let anyone know your name. We will not publish anything else that would let people know who you are. You can print a copy of this consent form for your records.

I freely give my consent to take part in this study. I understand that by proceeding with this survey that I am agreeing to take part in research and I am 18 years of age or older.

Social Behavioral  Version #  Version Date
1             05/07/2018