Quantitative Reasoning: Exploring Troublesome Thresholds

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Quantitative Reasoning: Exploring Troublesome Thresholds
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Abstract
Conversations about teaching and student learning with faculty across many of the science disciplines will invariably lead to a number of shared concerns. One such concern typically revolves around quantitative reasoning (QR). This paper presents the results of a pilot study in which instructors and students were interviewed with a view to identifying key QR obstacles in earth, ocean, and environmental sciences courses at one Canadian university. The instructor point of view was obtained by interviewing faculty and graduate student teaching assistants, while the student perspective came from a focus group of undergraduate students from across these disciplines. In both cases, participants were asked about specific quantitative aspects of their courses where students struggle and strategies they were already using in these cases. We examine the possible role of threshold concepts in QR within the earth, ocean, and environmental sciences. Threshold concepts are transformative, often troublesome concepts that are key to developing true expertise in a discipline; once mastered, they are irreversible and can serve to bring together different aspects of the subject. As such, their possible role in QR holds potential for enhancing the learning. Meyer and Land (2005) suggest that in crossing these thresholds into new ways of viewing the discipline, or indeed, the world, the journey is somewhat akin to travelling through a portal, or liminal space, where uncertainty is common and developing understanding is not necessarily linear. We further explore a number of strategies that can be used to help students overcome the challenges that were identified.

The results revealed a range of themes considered troublesome that crossed all disciplines including applying math across changing contexts, a fear of math, the lack of student’s ability to reflect on their answers and therefore correct where necessary, and working with conversions and scale. Additionally, both faculty and students identified the difficulty many students have when working with data, in particular, plotting data, manipulating data and interpreting results, with and without the use of computer software packages. We note in particular that students’ difficulty in articulating or identifying threshold concepts may reflect their incomplete journey through the liminal stage. We need other strategies, such as looking at their work, in order to assess this more completely. Although no group specifically articulated concepts, they considered transformative amongst the troublesome concepts they identified. We suggest that there are learning thresholds within QR, and that these span all the sciences. Two such thresholds we propose based on our study are: (a) the ability to apply QR across a range of contexts and use it as a tool or a form of language for scientific problem solving, and (b) fluency in data literacy which enables a student to work through the scientific process. We conclude by presenting a set of strategies to help instructors guide students as they develop QR skills while working through these troublesome areas. These
strategies include those suggested by faculty and students in this study, and others identified from evidence-based best practices in the literature.

**Keywords:** data literacy, scientific problem solving, quantitative reasoning skills, threshold concepts, math, higher education

**Introduction**

In any discussion about student learning in the earth, ocean, and environmental sciences, the conversation at some point inevitably turns to the difficulties students appear to experience with quantitative aspects of our sciences. What is equally interesting and informative from the perspective of addressing this concern, is that if we set everything up so students know what equation to use, what type of graph to plot, and/or what numbers to input, they can successfully compute and complete the assigned task. This suggests that it is not so much the numbers themselves as a fluency with the notion of reasoning within the discipline *through* numbers that is perhaps the problem – the concept of quantitative reasoning (QR) is at issue. Furthermore, it is not uncommon for students who struggle with QR to have successfully completed one or more free-standing mathematics courses. There is a misalignment in students’ basic mathematical knowledge and their ability to use this within their disciplinary contexts; in other words, the context in which the problem is posed matters (Hughes-Hallett, 2001).

We wondered what might be threshold concepts within QR. Specifically, threshold concepts are those troublesome concepts in a discipline that create blockages to deeper understanding (Meyer & Land, 2003, 2005), and without mastery of these concepts it is difficult to move into this deeper understanding of the discipline. Threshold concepts are also integrating and irreversible, suggesting that mastering such concepts in QR might be particularly beneficial to student learning. There has been little specific research on how to best facilitate student progress in relation to these potentially troublesome and transformative concepts within QR specifically. Addressing threshold concepts within QR from an interdisciplinary perspective of earth, ocean, and environmental sciences may further inform how best to support student learning around QR within the disciplines.

Davies (2006) argues for focusing on threshold concepts within a discipline when assessing students’ learning, because once they are mastered, these threshold concepts become part of the way of thinking like an expert within the discipline. This is particularly significant, as Boustedt et al. (2007) argue that it is possible for students to get through a course or even a program by adopting a surface approach to learning: in such cases, they may pass all the requirements without really understanding or mastering the discipline. Cousins (2006) suggests that the threshold concepts within a discipline should inform curriculum and program design. This has profound implications for the nature and value of a given program, and suggests that it is particularly critical that we identify these threshold concepts and ensure we help students work their way through them, if they are to become true experts in the discipline. Ryan (2014) has proposed the existence of threshold concepts that span the disciplines particularly in
relation to the earth and environmental sciences, and proposes that linking cognitive science with threshold concepts is important in developing strategies for helping students recognize patterns and make connections.

QR is essential for student success in moving from novice to expert in all science disciplines. Yet, many students struggle or become disengaged from learning when asked to “do math” (Quinnell, Thompson, & LeBard, 2013). As instructors, we expect that they have learned the appropriate mathematical skills in their math courses, but students are not always comfortable applying these mathematical skills within a disciplinary context outside of the math course (Quinnell & Wong, 2007). We considered that there might be aspects of QR that are threshold concepts, and that these might span the disciplines. If so, are there novel ways in which we should approach the teaching of these particular aspects from within the different disciplines? We wondered what assumptions students and faculty make about the nature of QR, and what we might learn from student and faculty narratives around issues of QR, particularly as this links to threshold concepts.

What do we mean by QR? The Association of American Colleges and Universities (AACU) defines QR as a "habit of mind," competency, and comfort in working with numerical data. Individuals with strong QR skills possess the ability to reason and solve quantitative problems from a wide array of authentic contexts and everyday life situations (AACU, 2010, p. 1). This definition is in keeping with that of Elrod (2014), who refers to the concept of QR as something separate from, but encompassing of, math (Table 1). Elrod suggests that QR resides at the nexus of the discipline, math, and critical thinking (Figure 1), and notes that QR “…requires students to think critically and apply basic mathematics and statistic skills to interpret data, draw conclusions, and solve problems within a disciplinary or interdisciplinary context” (Elrod, 2014, p. 2). In general, then, the idea that such quantitative skills are embedded within the discipline (or across the disciplines) expands the discussion of the quantitative to place it in a context-rich environment. We adopt the definition of Elrod (2014) in our study.

Table 1
Key Components and Differences Between Mathematics Sensu Stricto and QR*

<table>
<thead>
<tr>
<th>Mathematics</th>
<th>QR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power in abstractions</td>
<td>Real, authentic contexts</td>
</tr>
<tr>
<td>Power in generality</td>
<td>Specific, particular applications</td>
</tr>
<tr>
<td>Some context dependency</td>
<td>Heavy context dependency</td>
</tr>
<tr>
<td>Society independent</td>
<td>Society dependent</td>
</tr>
<tr>
<td>Apolitical</td>
<td>Political</td>
</tr>
<tr>
<td>Methods and algorithms</td>
<td>Ad hoc methods</td>
</tr>
<tr>
<td>Well-defined problems</td>
<td>Ill-defined problems</td>
</tr>
<tr>
<td>Approximation</td>
<td>Estimation is critical</td>
</tr>
<tr>
<td>Heavily disciplinary</td>
<td>Interdisciplinary</td>
</tr>
<tr>
<td>Problem solutions</td>
<td>Problem descriptions</td>
</tr>
<tr>
<td>Few opportunities to practice</td>
<td>Many practice opportunities</td>
</tr>
<tr>
<td>Predictable</td>
<td>Unpredictable</td>
</tr>
</tbody>
</table>
Note. *This table has been reproduced from Shavelson (2008).

Disciplinary context / Real world

Math

QR

Critical thinking

Figure 1. QR as the nexus of critical thinking, math, and the disciplinary or real world context (Elrod, 2014).

So what might be considered “basic math skills”? Rylands, Simbag, Matthews, Coady, & Belward (2013) interviewed mostly Australian life science faculty about quantitative skills, and concluded that, in addition to statistics, most of the math identified as required by faculty, was basic secondary school math. However, as might be expected, the details of what was incorporated as basic math varied depending on the specific courses involved. In addition to the recognition that the AACU gives to QR as an essential or key skill of undergraduate education, it is also considered one of the engagement indicators of the National Survey of Student Engagement, and the Higher Education Council of Ontario. Furthermore, Matthews, Hodgson, and Varsavsky (2013) acknowledge: “There is international agreement that quantitative skills are an essential graduate competence in science” (p. 782). Rylands et al. (2013) further note that international organizations lament the lack of quantitative skills in undergraduate science and continue their search for ways to improve the situation. We posit that it is not simply the lack of quantitative skills but rather the ability to reason quantitatively that poses the greater problem for most science students. Shavelson (2008) highlights the distinctions he draws between mathematics *sensu stricto* and QR (Table 1), and in his conclusions points in particular to the contextual nature of QR.

An additional consideration, therefore, is how we might approach the teaching of QR: Do we offer a course on QR or do we embed it within the disciplines, for example? Hughes-Hallett (2001) argues that QR must be taught in the context of the disciplines. She further contends that QR is more likely achieved through developing a common commitment to fostering across-disciplinary incorporation of QR. She further argues that the development of QR requires that we provide much practice for students. Furthermore, she contends that we will be more successful if we make QR part of the regular expectation of learning and working within our discipline(s).

Quinnell et al. (2013) note that many students bring math anxiety to their science studies. They suggest that perhaps instructors do not provide the necessary scaffolding for students as they transition from their separately-held math and
disciplinary knowledge to linking the necessary components of each. Matthews et al. (2013) found that life sciences students in particular self-report the lack of confidence in quantitative aspects of their science and they argue for a holistic approach to the teaching of QR across the science and math disciplines. They further suggest three implications from their study of students’ perceptions of their QR abilities: (a) the importance of building student confidence, therefore their self-efficacy and ability to succeed, (b) the benefit of professional development in teaching QR for academics teaching science students, and (c) developing a systematic approach in which the importance and significance of QR is highlighted in our teaching, so students can see both the present and future relevance of QR as they move beyond graduation. Matthews, Adams, and Goos, 2010 also note that using case studies and real world examples in teaching QR has a positive effect on students’ perceptions of their QR abilities.

It is against such a backdrop that we chose to undertake a pilot study focusing on the issue of QR within the earth, ocean, and environmental sciences, and in particular, with the hope of identifying threshold concepts within QR. The aim of the study was to answer the following question: Are there aspects of QR in earth, ocean, and environmental sciences disciplines that can be identified specifically as threshold concepts, and if so, how might these inform our teaching within and across disciplines?

Students entering post-secondary education commonly perceive these sciences as less quantitative than physics and chemistry for example, and they can be reticent to engaging in quantitative approaches as a result. We were interested in perceptions around QR across those involved in the learning environment in a Canadian context, and chose to interview faculty, graduate student teaching assistants (GSTAs), and to hold a focus group with undergraduate students. We chose to use similar questions for the interviews with the faculty and the GSTAs and the student focus group in an attempt to tease out any significant differences or similarities in perceptions around the issues of QR between faculty, GSTAs, and students.

**Methodology**

All participants were invited to participate in the study by the researchers via email. We invited senior undergraduate students to participate in a focus group and five instructors and five GSTAs to participate in individual semi-structured interviews.

**Student Focus Group**

We nominated senior students from earth, ocean, and environmental sciences undergraduate programs who could reflect on their learning experiences over the course of their degree program. The student focus group (n=8) met on two separate occasions, and each meeting lasted around one hour. See Appendix A for the list of questions. Each session was tape recorded and subsequently transcribed.

**Teaching Faculty and GSTA Interviews**

We held ten semi-structured interviews with teaching faculty (n=5) and GSTAs (n=5) from earth, ocean, and environmental sciences courses. Participants were
purposively selected as those who teach courses in earth, ocean, and environmental sciences at the introductory or second year level with the exception of one GSTA who taught at the third year level. All courses taught by the faculty and GSTA included both a lecture and a tutorial or laboratory component. GSTAs were asked to reflect on both their own experiences during their undergraduate programs as well as their more recent teaching experiences at the university. Both researchers were present during the interviews and took notes. The researchers reviewed their notes together shortly after each interview to ensure all information was captured and recorded accurately.

**Data Analysis**

Responses for each question from both the focus group and the interviews were broken down into individual comments and entered into an excel spreadsheet with each comment being assigned to one line. The comments from the interviews were also linked to each individual from whom they came. Once all comments were entered into the spreadsheet, both researchers independently looked for common themes across the responses. Then together through an iterative process both researchers agreed on common themes that would be used for the remainder of the analysis. Each comment was subsequently assigned to one of these themes.

The number of participants that referred to each theme was tallied to highlight the level of consensus around each theme. Additionally, we present some of the broader themes by the overall number of times that an idea appeared in the transcripts. We normalized the comments made in the focus group to a value out of five based on the level of discussion on any one theme. We assigned 1 to a theme mentioned once, 2.5 to a theme mentioned more than once, and 5 to a theme that was a key point of discussion among the majority of students in the focus group. This allowed for comparison with the number of times a theme was mentioned by the five teaching faculty or five GSTAs.

**Results**

Students, faculty, and GSTAs were readily able to identify troublesome aspects as well as strategies and tools that they used to help address these troublesome aspects. However, they failed to identify, or at least articulate, consistent themes around eureka or insightful moments, or transformative concepts that would lead to a broader understanding within and across the disciplines. We summarize our findings about the troublesome concepts and on strategies and tools used to address these.

**Troublesome Areas of QR**

The aim of question 1 in our survey was to help us identify areas of QR that students found troublesome. Several themes emerged from the faculty and GSTA interviews and the undergraduate focus groups. Participants across the three groups commented on a number of themes, while some themes were only commented on by two or unique to just one group. The themes crossed all three disciplines of earth, ocean, and environmental sciences. Figure 2 provides an overview of the results.
Figure 2. The major problem areas with respect to QR as reported by faculty, GSTAs, and senior undergraduate students at Dalhousie University. Undergraduate responses are grouped as 1–theme mentioned once, 2.5–theme mentioned more than once, and 5 – theme was a key point of discussion among the majority of students in the focus group.

**Fear factor.** Both GSTAs and faculty commented on some students experiencing a fear of math. One faculty member commented on the wide range of comfort levels with math in their course. Whereas some students enjoyed the quantitative components, others shut down and stopped listening when a disciplinary problem was approached mathematically. These students were reported as saying “I can’t do math.” Several participants commented that it was most often the Arts majors in the courses who resisted doing math. One faculty member commented that many students did not see math as a language or as an efficient tool that can be used to express ideas and conclusions around scientific questions and problems, and rather they feared math and saw it as a barrier to learning science.

**Switching contexts.** Both faculty and GSTAs commented that students struggled in applying quantitative skills learned in one science course to another. Even within the same course, if the context changed significantly, students struggled trying to figure out how to approach a problem quantitatively. In particular, faculty commented on students’ inability to apply knowledge and skills learned in an introductory statistics course to problems within the disciplinary context of environmental science or oceanography. One faculty member referred to students often having a hard time...
thinking of math as a tool that can be used in many different ways and not just as a recipe to follow in only very specific situations.

**Understanding math.** Both faculty and GSTAs commented on students’ lack of understanding of what the quantitative results mean, especially when thinking about the meaning of the bigger picture within the discipline. For example, comments were made about students struggling with the meaning behind basic statistical tests including the meaning of a normal distribution.

**Conversions.** All three groups commented on students struggling with conversions. For example, students struggled trying to do calculations with ratios including working with distance scales on a map or converting between different units.

**Student reflection.** Faculty and GSTAs mentioned that students often rush through their quantitative calculations without taking time to reflect on the meaning of the assignment and whether their answers were reasonable or even feasible based on the given data. The instructors were concerned that the students were missing the bigger picture or real world implications of the quantitative problems they were solving. For example, students did not contemplate the implications when their answers were incorrect by one or even two orders of magnitude.

**Graphing and statistical software.** All groups commented on the struggle with graphing and students not knowing which type of graph or diagram was most appropriate for the data being analyzed, or why one particular type of graph would be more appropriate than another. As part of these discussions, and additionally in relation to working with data and statistics, participants commented on how learning to use software packages, such as Microsoft Excel, R, and Matlab, presented its own challenges. Participants commented that students were not always given specific instruction on using the software, which created a barrier to learning how to create graphs and carry out statistical tests. One student commented that this assumption instructors make, namely that students know how to use the software, created a stressful learning environment when they were trying to learn data analysis methods.

**Data literacy.** Statistics and data handling were major points of discussion in the undergraduate student focus group, and were also commented on by three faculty members and two GSTAs. Many of the comments during all interviews and focus groups can be grouped into the broader theme of data literacy. We analyzed our results to see how many comments were made within this broader theme and specifically about: (a) using software to work with data, (b) the students’ ability to visualize what they were trying to do with the data, (c) their ability to manipulate the data in order to create that visualization, and finally, (d) students’ ability to interpret the results. Figure 3 shows the outcomes of this analysis.
Participants spoke about students struggling to work with data and in particular to work with data software, being able to visualize what they were trying to do, how to manipulate the data to create the visualization and then finally how to interpret their results.

**Strategies and Tools that are Used by Students and Instructors to Address Troublesome Aspects of QR**

There were a wide range of tools and approaches being used by students, GSTAs and faculty to address these troublesome areas of QR. The main themes that emerged from the interviews and the focus group are presented in Figure 4. Most significant, as identified by students and instructors, are the need for reflection, the use of visualization, and the importance of practice. These three were followed closely by the usefulness of incorporating real world applications, and the benefits of group work.
Discussion

Keeping in mind the small sample size of this pilot study, a number of key issues emerged during our discussions, and we focus on four in particular here: (a) commonality and disparity between the student perception and the instructor perception, (b) the common identification of the key role of working with data, (c) the possible existence of learning thresholds within QR, and (d) strategies for teaching QR.

Instructors and students did identify a number of troublesome areas in common. However, students focused on the use of statistics as a particular problematical area, and did not explicitly identify the process of science, multi-step problems, switching context, or understanding math as troublesome areas: on the other hand, these aspects were identified by instructors (Figure 2). This in itself is informative. It may be that with the expert “bigger picture” view, instructors see these broader areas and contexts as significant barriers, whereas the students, as novices, focus on the specifics and the details. Both novices and experts identified conversions, scale, computer software, and graphing as troublesome: all of these are more concrete, and therefore readily identifiable by novices as well as experts. What is particularly clear from the responses is the widespread recognition that working with data and graphs, whether computer-aided or by hand, is a key troublesome area perceived by both instructors and students alike. This may in part reflect the widespread use of this aspect of QR across these disciplines. However, it also raises the connection between numbers and space, a connection that Willingham (2009) argues seems to be innate in humans. If this is
indeed the case and we have an innate ability to make connections between numbers and space, is it possible that there is some sort of a gap in the way in which we are teaching graphing? Because this came out so strongly in all interviews, it is worth a little more exploration here.

Figure 3 speaks to the perceived troublesomeness and difficulty of data interpretation as identified by students as well as by instructors. Whereas students and instructors identified software, data manipulation, and interpretation in our conversations, only instructors specifically talked about data visualization. It may be that visualization is not a strategy that students consider when attempting to reason quantitatively, and this suggests it is one we may want to make more explicit in our teaching. While learning and knowing how to use the software were barriers to effective QR, they are in themselves not QR, however, manipulation and interpretation of data can be considered within the QR realm, as they are effectively components of critical thinking (Figure 1). Indeed, Facione (2015) recognizes interpretation as one of the six key aspects of critical thinking, highlighting its importance in QR.

Both the instructors and the students in our study, together with a number of researchers (Elrod, 2014; Hughes-Hallett, 2001; Willingham, 2009) speak to the need for practice and reflection in learning and mastering QR, or indeed, mathematics in general (Wheatley, 1992). One faculty member in our study talked about how they provide such practice “... working with the same concept in different ways: home reading, lecture discussion, quiz, then application.” Another spoke of how important it is to ask students “is this reasonable?” or “do you believe that?” frequently as they work through their practice in applying quantitative skills. In other words, the importance of deliberate practice, where the student is focused on practicing with a view to improving and learning, and where they receive formative feedback, is critical (Ericsson, Krampe, & Tesch-Römer, 1993). This faculty member further noted that students struggle to pick out key things in their data and data representation; they tend to look at the line on the graph, and not at the axes, or the context. Yet another noted the importance and usefulness of having students work with “real data, real applications; how real scientists do things.” These ways of encouraging reflection, having students stop in the moment and think about what they are concluding, are considered vital by faculty and GSTAs for developing better understanding, and are supported by the conclusions of Wheatley (1992) and in a broader sense, by the work of Dewey (1916).

With respect to group work, both instructors and students identified this aspect as important. Research by Springer, Stanne, and Donovan (1999) concluded that collaborative work in the STEM disciplines did indeed increase understanding, suggesting that this is a strategy that we might adopt to increase the level of QR in undergraduate science. Interestingly, Ernie, LeDocq, Serros, and Tong (2009) draw attention to the link between collaborative learning and students’ improved communication in math, highlighting the idea that in collaborative work, students use the language in speaking and explaining their work and ideas to others.

A threshold concept is not simply a troublesome one, but also one that once learned transforms a student’s thinking within and about a discipline (Meyer & Land, 2003). The participants in our study did not articulate any specific troublesome areas
that they saw as transformative within their discipline. Students, in particular, had difficulty in articulating or identifying threshold concepts, which may reflect their incomplete journey through the liminal stage. Thus, although our pilot study led us to a range of troublesome concepts associated with QR, in addition to tools and strategies that we can use to help students master those concepts, it did not clearly identify which were threshold concepts.

Based on our findings, we propose that if we remove the disciplinary boundaries of earth, ocean, and environmental sciences, and broaden our discussion of threshold concepts in QR to a student’s understanding of the process of science, that we have identified two key “learning thresholds” (Land, Meyer, & Baillie, 2010, p. xxviii) which are essential to moving from a novice to an expert scientist. First, the ability to apply QR across a range of contexts (within or across disciplines) and using QR as a tool and as a form of language used in scientific problem solving is in itself transformative in a student’s understanding of the process of science. Second, fluency in data literacy more readily enables a student to work through the scientific process. Perhaps the ability to conduct a research project (data collection, manipulation, visualization, interpretation) would be an indicator of the movement from novice to expert, and would include transformative thinking around the process of science. We propose that rather than simply being associated with earth, ocean, and environmental sciences, there may be threshold concepts or learning thresholds within QR that are essential to students’ understanding of the process or nature of science across all science disciplines, and that being able to apply QR across a range of contexts, and being data literate are two of these learning thresholds.

We would like to continue our research on threshold concepts and their link to learning thresholds within QR and further investigate which of the specific troublesome concepts are also transformative. This may involve taking a step back from the troublesome concepts and focusing on identifying those that are transformative, and then comparing the two. We plan to investigate learning outcomes and assessments with a view to identify troublesome and transformative concepts and skills associated with QR. We would hope to measure student movement from novice to increased expertise as portrayed in their work, and continue with developing strategies that might better enable all students to cross these thresholds.

**Conclusion**

Whereas our pilot study looked at the perceptions of a small number of instructors and students, we were able to identify a range of troublesome areas of student learning around QR and we have demonstrated a need to be more explicit and deliberate in our efforts to increase QR among our undergraduates in the earth, ocean, and environmental sciences. In particular, we need to work on increasing our efforts in providing opportunities for students to practice using QR in real-world situations, together with heightened attention to effective student collaborative work in QR embedded within and across the disciplines. These efforts will increase student facility with QR. Additionally, creating opportunities for reflection, both verbal and in writing, will further enhance our efforts, and as Hughes-Hallet (2001) notes, we will be more
successful if we work together across disciplines to develop a learning environment in which QR is not only expected, but the level at which students attain it is heightened.

A key finding of our study was the identification of learning thresholds within QR, and that these span all the sciences. Two such thresholds we propose are: (a) the ability to apply QR across a range of contexts and use it as a tool or a form of language for scientific problem solving, and (b) fluency in data literacy which enables a student to work through the scientific process. We further conclude that students have difficulty in articulating or identifying threshold concepts, perhaps because they are still working through the liminal space as they grapple with QR within their disciplines. Thus, a better way to identify threshold concepts would be through an analysis of their work. It still remains to be established specifically which troublesome concepts are key in terms of thresholds students must pass through to move from novice to experts within their disciplines.

Acknowledgements
Anonymous quotes from instructors, GSTAs, and students are used with permission and gratitude. The study was conducted with research board approval from Dalhousie University.

References


Appendix A
Survey Questions

Quantitative Reasoning: Crossing Thresholds: Questions asked of instructors, GSTAs, and students for which there were similar recurring responses and consistent themes.

We are interested in your perspective on aspects of undergraduate student learning in science and how this might inform our teaching. We are particularly interested in your insights around aspects of quantitative reasoning. In “quantitative reasoning” we are including anything connected to math, equations, calculations, graphing, scaling, mapping, numerical data, etc.

1. In your experience, what have you found to be particularly troublesome aspects in quantitative reasoning and why do you think these were particularly troublesome?

2. Can you identify any “eureka” or “a-ha” moments that students have had, and around what concepts? How did these relate to your answer to the first question...

3. Of the troublesome concepts, were there any that you found that, once students “got it”, it made a big difference to their understanding within the discipline? (How about across other (science) disciplines?)

4. Based on your own experience, what kinds of approaches or tools do you think were most helpful as your students moved towards mastery of the concepts? What role, if any, does visualization play, for example? (These could be teaching aspects, something you did yourself, working with a peer, etc...) Are there things that you think could have helped students achieve these insights sooner?