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

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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.

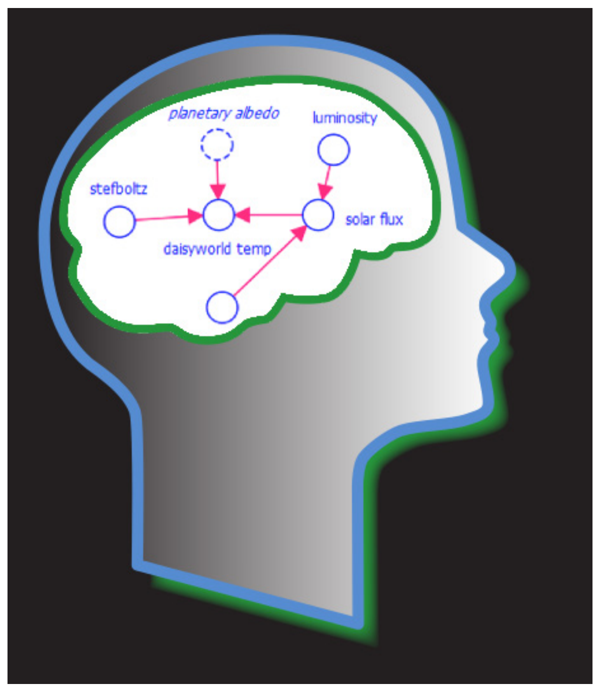

Figure 1. Computational models, such as the STELLA Daisyworld model shown in this diagram, aim to help geoscientists figure out and describe how the world works. Components are identified and linked to explore quantitative relationships of cause and effect and feedbacks, evaluate system behavior, and make predictions. Effective teaching with models benefits from cognitive research on the use of models. Figure created by Dana Chayes.

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.

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).

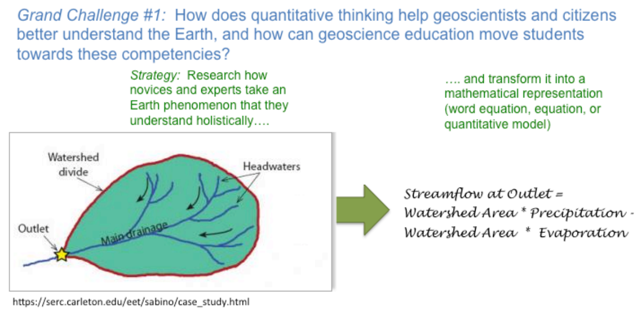

Figure 2. Illustration of the process of transforming holistic understanding of a situation or phenomenon into a mathematical representation.

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).

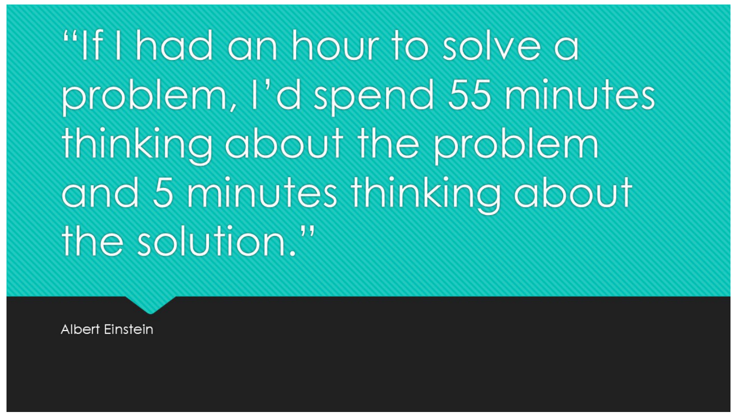

Figure 3. Defining authentic problems is not easy, but is the first critical step to solving them.

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 oppsed 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.

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Figures

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

Figure 2:
Provenance: Kim Kastens, Columbia University in the City of New York

Figure 3:
Provenance: Kristen St. John, James Madison University