Transdisciplinary Science Education Research and Practice: Opportunities for GER in a Developing STEM Discipline-Based Education Research Alliance (DBER-A)

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INTRODUCTION

Each science, technology, engineering, and math (STEM) discipline has developed a rich, ongoing program of education research and scholarship of teaching and learning (SoTL). Recent interest in connecting separate threads offers some exciting opportunities. In an effort to clearly communicate the new opportunities for science education and practice, we present ideas, implications, and foundational basis without the familiar citations that provide attribution in the surrounding text. Instead, we provide a reference list at the end that is organized by section for the reader to peruse the primary resources and other commentaries that help support the intellectual foundation of this editorial. We consider the opportunity for science education research and practice broadly, the intellectual opportunities available from outside geoscience education research (GER), the value of GER to the broader program, and finally thoughts on next steps.

Education research that has focused on STEM education has been referred to collectively as discipline-based education research (DBER). DBER focuses on (1) how people learn concepts, practices, and ways of thinking within STEM disciplines; (2) characterizing the nature and development of expertise in disciplines; (3) measuring instructional strategies that advance student learning; (4) guiding the incorporation of research findings into classroom practice; and (5) identifying inclusive approaches to STEM education. Developing in parallel with DBER, the field of SoTL focuses on supporting instructors as reflective teaching practitioners who use evidence-based and evidence-informed methods and share these methods with other practitioners to support a community of scholarly instructors. A useful distinction between DBER and SoTL lies in the goals of each: DBER seeks to increase the theoretical and empirical knowledge base of teaching and learning in a discipline, whereas SoTL seeks to improve the effectiveness of individual teachers and the use of evidence-based curricula or pedagogy. However, there is no firm boundary between DBER and SoTL, with many individuals working in both communities.

The geosciences education community has explicitly included both DBER and SoTL under the umbrella term "geoscience education research (GER)" because these approaches to learning contribute to positive feedback loops, with each providing important intellectual resources for the other. For example, SoTL can identify promising practices and puzzling questions that are important and suitable for education research, as well as point to pedagogically grounded research priorities. DBER can study these issues to test or generate theory that may inform or improve practice, and SoTL can use theory and findings to improve or transform practices in the learning environment and provide guidance to instructors on the value of new practices, as well as how to implement them. The integration reflects the value of a bringing together theory and practice in a trading zone to advance both theory and practice. This trading zone supports the nontrivial problem of applying theories to classroom, field, and lab settings in design-based education research and the theoretical payoff for applying research to real-world problems. It is critical to recognize in this idea that we are not suggesting DBER is applied research; DBER research spans the range from deductive theories to case studies. What we are pointing out is the value of a cycle of progress that is supported by improvements in theory and practice.

We speculate that the geosciences may be particularly open to combining theory with individual practice because of the important roles that case studies (e.g., a single outcrop or a specific field location) can play in furthering theory in disciplinary science and, conversely, the important role that theories about Earth in general (e.g., plate tectonics) have in interpreting the geoscience of a specific location on Earth. In addition, in recent surveys of the GER community, most respondents indicated that they both (1) develop and apply new geoscience teaching innovations and curricula and (2) develop or test GER questions and hypotheses. This suggests that many members of the GER community move fluidly between SoTL and DBER and thus between practice (or implementation) and theory.

In contrast, as recounted in a National Research Council (NRC) report, the broader STEM DBER and SoTL communities have largely developed in isolation, resulting in separate journals, conferences, and communities of practice. Although DBER can be traced back to the late 1800s, it gained recognition as a modern field within parent science disciplines in the 1970s to 1990s. Physics education research (PER) is generally recognized as the most mature DBER field, having emerged in the late 1950s and 1960s as a

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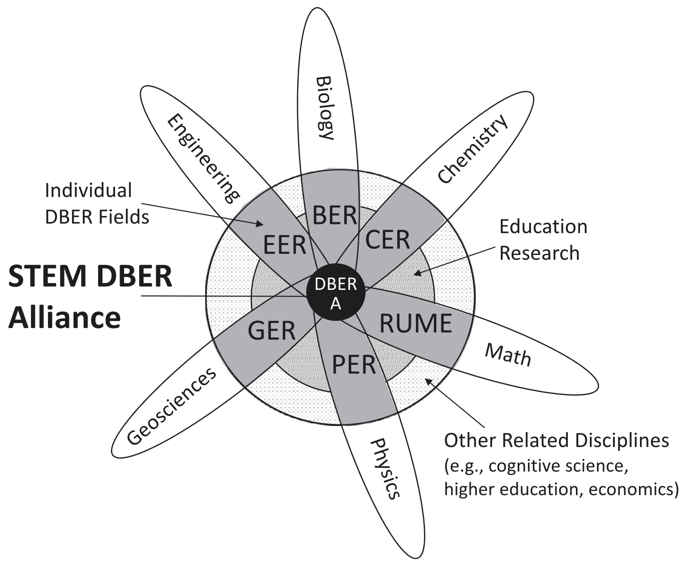

FIGURE 1: Visualization of the intersections of the various DBERs with education to overlap in an alliance. Image based on an initial conceptualization by Mark Connolly and published in Henderson et al. (2017). Copyright American Society for Engineering Education. Reproduced with permission.

product of K–12 curricular reforms driven by Sputnik and the space race. By the 1980s, about a dozen universities offered a doctoral degree program in PER. In 1999, the American Physics Society formally recognized PER as a subdiscipline within physics and established a PER-specific journal in 2005. The development of chemistry and math education research largely parallels that of PER, with engineering, environmental science, biology, and astronomy education research, as well as GER, emerging as recognized fields in the 1990s to 2000s.

In our field, the *Journal of Geoscience Education (JGE)* has published predominantly SoTL papers since its inception in 1951 but saw an increase in DBER studies in the last two decades. These were formally divided into Curriculum & Instruction and Research articles in 2010 partly in recognition of the growth in geoscience DBER. Growth of new geo-DBER fields continues, with atmospheric and climate science education emerging in the past few years.

Within the past few years, researchers have begun to call for improved integration of the broader DBER communities to address persistent issues of STEM-wide teaching, learning, inclusion, and institutional change. In response to the call for increased collaboration between DBER fields and prior cross-DBER meetings, researchers from math, biology, chemistry, physics, geoscience, engineering, economics, education, and psychology came together in May 2017 at the Howard Hughes Medical Institute (HHMI) to explore the potential for a STEM DBER alliance (DBER-A). As with a preliminary 2016 meeting, this May meeting was supported by HHMI, the National Science Foundation (NSF), the Association of Public Land Grant Universities, and the American Association for the Advancement of Science (AAAS). The goals of the workshop were to consider three broad questions: (1) What are the grand challenges for DBER? (2) What organizational and communication structures will best support DBER-A? (3) How will DBER-A interact synergistically with existing organizations operating in related spaces? As attendees and a co-convener (St. John) of this workshop, we wrote this commentary to initiate dialog on the potential opportunities that a STEM DBER-A may offer to GER community members and the community's research and education programs and highlight important contributions that GER can offer to such an alliance.

WHAT OPPORTUNITIES ARE AFFORDED BY A CROSS-DBER-A?

Two Conceptual Models

A summary of the DBER-A opportunities published in the August issue of *JGE* recognizes that DBER-A offers value at various levels of interdisciplinary activity, from borrowing research methods and theoretical tools from other fields to allowing research on necessarily interdisciplinary issues, such as identifying learning principles that transcend specific STEM disciplines.

One vision of the opportunities afforded by an alliance is reflected in Figure 1, a diagram developed by the workshop conveners to illustrate the goal and challenge of bringing together the various DBER research communities to the place where they overlap (the circle labeled DBER-A). Whereas visually the circle is small, it represents the important achievement of connecting educational concepts across disciplines in which research can reveal knowledge germane to all STEM education.

Here, we offer an alternative visualization of this achievement (Figure 2) that considers the potential change in knowledge over time, thus recognizing that the circle in Figure 1 is a stem that connects and collects from all root disciplines. In the tradition of geoscience, Figure 2 illustrates change over time (lower is older) as DBER comes to a central trunk where knowledge across disciplines is connected (present day is the horizontal line). DBER-A draws from across the academic landscape, and perhaps orthogonal to this cross section, and thus not seen, would be roots feeding in from cognitive science, education research, economics, computer science, and the arts. Also absent are the disciplinary SoTL roots; however, the unified trunk benefits from, and may require, integrating SoTL.

The tree diagram includes prediction of distinct phases, because forming a DBER-A will not be a magical transformation that occurs in an instant. We anticipate a possible phase in which attempts to integrate concepts across DBER result in accommodations that reduce redundancy or restrict theoretical accounts that were overly broad. The eventual opportunities may include extracting general concepts that transcend disciplines, improved research methods so that assessment instruments and analytical tools are validated for use across multiple STEM disciplines and institutions, increased breadth of change of student learning, improved instructor professional development and practice to broaden student learning, new practices in curriculum development and implementation, new institutional approaches to educational research, better support for diversity and inclusion, and new and fulsome support for learning across the human life span (from young student to retired learner) that combines informal education, traditional education, and

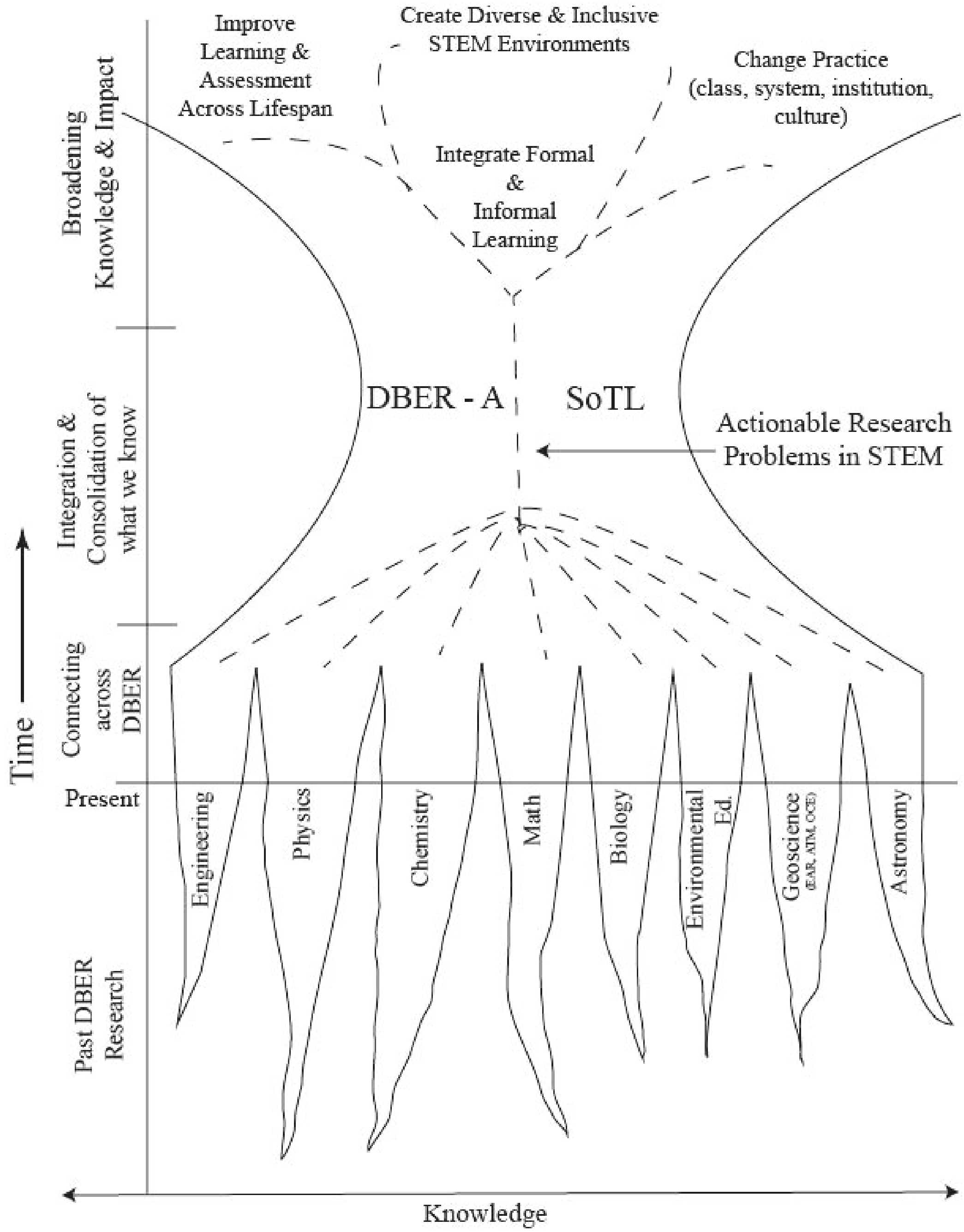

FIGURE 2: A visualization of the time course of merging research and practice knowledge across the STEM disciplines to support broader knowledge and impact.

professional development and provides integrated career development from student to professor.

There has been little recognition of the intellectual opportunity inherent in combining disciplinary science knowledge with an understanding of how humans learn. The STEM disciplines work to describe the world around us. DBER, like psychology and education, seeks to describe how the mind learns about the world directly and indirectly, formally and informally. By understanding the learning challenges and the potential for learning, the DBER-A may support the entire developmental trajectory of learning about the natural world, from informal education through K–12, undergraduate, graduate, postdoctoral, and on, including career phases traditionally not conceived of as learning: early career, midcareer, and late career, as well as retired disciplinary scientist.

Collaborations within DBER-A might be characterized as intellectual cross fertilization; here, the analogy is to a largely passive model in which a meme, once inserted into the discipline, will proliferate. We propose an alternative analogy, reverse outreach, in which important knowledge and important goals from a foreign discipline are deliberately imported. The imported knowledge may offer a new perspective to develop research on important but previously unrecognized areas, and the imported goals allow coordination of priorities for researchers to aid in research and practice across STEM. For example, the geosciences have been particularly successful in developing community-wide professional development programs that have resulted in the creation of a deep collection of teaching resources and measurable changes in instructional practices. Other disciplines may find value in adopting some of these strategies. Reverse outreach better captures the need for work both in translating familiar concepts for others to understand and in providing the opportunity to learn something big and important from another discipline, while recognizing the difficulty and effort required.

A Starting Point for Integration

We have organized our editorial to consider both opportunities for GER to inform the broader STEM DBER fields and ways in which interaction and collaboration with researchers in those fields could benefit GER, recognizing that these reflect two halves of a positive feedback loop. We begin with outcomes and ongoing efforts from the GER community, because we see this as a starting point for looking at areas of overlap between GER and the broader STEM DBER community, as well as looking at GER's strengths and unique qualities among the STEM disciplines.

Over the last three years, through a series of workshops held at the Earth Educators' Rendezvous, the GER community has been examining the current state of our research and considering the best course forward so that this research can have the greatest collective impact on advancing teaching and learning in the geosciences. Table I outlines one part of this effort. It highlights nine research themes on undergraduate geoscience teaching and learning that have been identified as important to geoscience education researchers and educators. In examining these GER themes, we recognize that there are many areas of alignment with issues and topics important to one or more other STEM fields; we point out some areas of potential cross-STEM DBER connections in the corresponding column. For example, teaching about Earth in the context of societal problems likely has overlap with the field of bioscience education (e.g., ecology education and sustainability), and most STEM fields struggle with issues of access and success of underrepresented groups. Several of the themes (indicated by a footnote in Table I) were specifically discussed by interdisciplinary working groups at the cross-DBER meeting in May. In areas of alignment, there are therefore opportunities for extending our knowledge and research practices. We address opportunities for these in the next sections.

WHAT ARE THE POTENTIAL DBER-A OPPORTUNITIES FOR GER?

The DBER community within the geosciences is smaller than those of several other STEM DBER disciplines. There are both benefits and challenges to our more modest scale. On the one hand, we have a greater proportion of common instructional experiences and curricula and can readily share and adapt resources among community members. On the other hand, we lack both the size and the disciplinary diversity of some of our sister disciplines, perhaps making us less likely to discover original approaches to DBER challenges. Some potential benefits of participating actively in a DBER-A initiative are as follows.

Expand Community

By linking individual researchers across DBER, lone scientists working on GER within a geosciences department can get support in the form of collaborators or mentors from another local DBER practitioners. One way to link such individuals would be through research problems that transcend individual STEM fields (Table I). Such an approach to matching would help provide intellectual resources and community support for other small, young research communities (e.g., engineering education research and atmospheric science education research).

Expand Resources

GER should leverage work in other DBER fields. We use the term "work" to encompass the array of intellectual products that support education, including theoretical concepts, typologies of learning and learning challenges, research designs and methods, assessment theory and instruments, models, design practices, data, teacher learning, misconceptions, and evidence-based and evidence-informed practices. For this to happen, GER community members need to know who does what in the different DBER fields. We can share summaries of what each discipline can contribute to DBER through disciplinary journals, conferences, and other sources (e.g., GER Division newsletters). In this way, GER could expand resources without having to bear the full cost (money and time) of investing in infrastructure, and DBER-A guidance could accelerate progress toward GER's goals. For example, the DBER-A already has a community-sharing online presence via the AAAS Trellis site, but it is underutilized. Organizing topical interest groups within the site would be one way to share resources. The value of sharing is evident in the recognized need for a central repository of DBER instruments and surveys and a database for DBER results; these could transform GER research and all STEM DBER research. Such an infusion of knowledge and infrastructure would support expansion of diversity and increase inclusion in GER and across STEM disciplines, including institution types (e.g., 2-year colleges and historically black colleges and universities). The GER Toolbox has an initial collection of instruments and surveys, as well as analytical tools used in GER and related fields, and has the potential to expand, but there is no repository for GER or broader DBER data. Having one would help increase the potential for meta-analyses, which is one way to increase the strength of evidence for GER claims.

Expand Intellectual Scope of Research

By considering problems across fields, one may characterize research questions in ways that transcend disciplines, identify research questions that are not visible within a single discipline, and use important ideas from other disciplines. The GER community is considering as a group what the overarching research questions are that define our field, their priority, and how best to support engaging in that research. Comparing the GER research priorities to those of other STEM DBER fields should help us advance GER research on themes that transcend STEM disciplines. In addition, DBER-A research priorities may highlight areas that the GER community has not yet identified as important

TABLE I: Possible areas of GER alignment with other STEM-DBER fields.

GER Themes	Potential Cross-STEM DBER Connections
Students' conceptual understanding of the solid Earth Science content (e.g., misconceptions and how to teach particular concepts and systems)	Complex systems permeate the natural world. Understanding students' conceptual understanding of components and linkages between components crosses discipline boundaries. Bioscience (e.g., ecology) may have significant overlap, as does engineering (e.g., sustainable engineering).
Students' conceptual understanding of the fluid Earth Science content (including ocean, atmosphere, and climate) and environmental content (e.g., misconceptions and how to teach particular concepts and systems)	
Teaching about Earth in the context of societal problems (e.g., resource use and sustainability)	
Elementary, middle, and secondary Earth Science teacher education (i.e., working with teachers and future teachers in all settings)	Quality K–12 STEM education depends on high impact education and training of pre- and in-service teachers.
Access and success of underrepresented groups[1] in the geosciences (i.e., diversity and broadening participation)	All STEM fields struggle with issues of access and success of underrepresented groups.
Cognitive domain and problem solving[1] in geoscience courses (e.g., quantitative reasoning, temporal reasoning, spatial reasoning, and use of models)	Most sciences and math require visualizing and reasoning about unfamiliar scales and spatial and temporal patterns.
Instructional strategies[1] to improve geoscience learning in different settings and with different technologies (e.g., place-based instruction, teaching large lectures, and online instruction)	STEM education draws on a range of teaching settings, from field-based learning in ecology to lab-based learning in chemistry. All share the challenge of teaching large lectures and the expansion of online learning.
Geoscience students' self-regulated learning or metacognition and affective domain[1] (e.g., attitudes, motivations, and values of students)	Negative attitudes and a diminished value of science in society are issues that can affect all science fields, especially in introductory courses.
Institutional change[1] (e.g., geoscience programmatic change), faculty professional development[1] (e.g., faculty workshops), and teaching assistant training	Professional development is a primary conduit for translating STEM education research findings into practice.

[1]Themes specifically discussed by interdisciplinary working groups at the cross-DBER meeting in May.

directions for research. For example, questions such as how concepts that transcend disciplines (e.g., systems, scale, and patterns) can be integrated into curricula to connect knowledge across domains and how a scientific identify is formed were raised in the context of STEM DBER-A meeting.

Expand Reach

DBER-A may improve our skill in outreach and a forum for communicating findings to a larger, and interested, audience, increasing the impact of GER findings. A richly cross-linked DBER-A community would read and cite GER research in *JGE* and other publications. The GER community has published good work, and it is not widely cited. For example, literature reviews from the November 2017 issue of *JGE* (Synthesizing Results and Defining Future Directions of Geoscience Education Research) could be widely shared.

Improve GER Education

Critical to successful education improvement are integrating research and practice to support a cycle of applying education research in context and drawing from education practice to create and refine powerful learning theories. Interacting with DBER-A may facilitate application of theories of learning to GER education. With the expansion of GER in the last several years, the opportunity to develop graduate GER programs has also provided a need to design training and curriculum for students pursuing GER graduate degrees and research. Interacting with DBER-A may help to provide information about how other more long-lived DBER communities have designed their graduate training programs and may offer opportunities for some common training (e.g., research method courses).

WHAT MAKES GER A POWERFUL ENGINE TO ADVANCE THE GOALS OF A CROSS-STEM DBER-A?

We encourage developing connections with DBER and SoTL researchers across the sciences to realize the intellectual and community value of engaging with researchers outside of GER. We anticipate that developing these connections may be facilitated by clearly articulating what opportunities GER offers the broader scientific community for understanding and improving science education. Here, we review four observations about the essential nature of geoscience and geoscience education that may be obvious to geoscience practitioners but may not be evident to colleagues in other STEM disciplines. We review each of these principles to provide readers with a resource for developing personal, one-on-one relationships with others interested in science education.

Geoscience Illustrates the Power of Well-Integrated Education Research and Education Practice

Our sense is that some STEM disciplinary education societies focus primarily on education research, but not practice. This division may reflect an intellectual prioritization that misses the opportunity to combine DBER and SoTL. Combining theory and practice is a powerful means to advance both domains and may be necessary to unify the root disciplinary research divisions, as envisioned in Figure 2, into a productive whole. The National Association of Geoscience Teachers (NAGT) has a division that is dedicated to education research (the GER Division). Within the geosciences, workshops and conferences combine researchers and instructors (e.g., Encouraging Networks Between Geoscience and Geoscience Education and the Earth Educators' Rendezvous). Such venues may provide a useful model for others and may help make explicit the value of both research and practice, implicitly making the case for avoiding intellectual snobbery that has the potential to distance research findings from the very population that we would want to incorporate them into classes.

Geoscience Provides New Insights About Inductive Reasoning and Learning in Science

Historical sciences progress with different reasoning than employed for an experiment. The training and thinking that are required for a historical science are important perspectives in science. Many notable characteristics of geoscience arguably follow directly from the practical and logical character of research grounded in the current Earth about which we do not get to run experiments. Earth data are unusual in science in that variables of interest are not under the control of the scientist, so inferences must be made from complex patterns. Clear inferences often require finding the right location to collect data that allows inferences. Other sciences may recognize that they too may face research problems about which they cannot conduct experiments.

Geological observations are collected in the field, often in a group of scientists with diverse skills who have come together to work on understanding the past using a variety of approaches. Teaching and learning in the field (outdoors and doing science fieldwork) has a unique intellectual and socioemotional character. Principles of field-based learning are just beginning to be developed in GER. However, it is often not obvious how to translate what works in the classroom to the field. Work in this area may be of interest to other STEM fields as they work on learning in unstructured settings. Other historical and field-based STEM disciplines that may benefit from the application of GER findings include ecology and astronomy.

Geoscience Provides a Variety of Spatial, Temporal, and Systems Reasoning Challenges and Articulates the Logic of Spatial and Temporal Reasoning

All theories about the past Earth are based on inferences from observations of traces left by past events. These traces often take the form of complex spatial patterns. Thus, sophisticated spatial and temporal reasoning is required to understand and practice geoscience. The need to visualize and discuss objects and processes outside of direct experience requires understanding and challenging of three-dimensional (3D) visualizations (e.g., topographic maps and block models) and then reasoning with them. The widespread use of visualizations is hardly unique among STEM; however, GER is a rich source of challenging spatial learning problems: reasoning at multiple scales, inferring 3D structures from two-dimensional patterns, inferring spatiotemporal events from their spatial traces, the range of individual differences in spatial reasoning, and communicating 3D and four-dimensional (4D) information using disciplinary terms of art, gesture, and sketches. That geoscience requires explicit reasoning about 3D and 4D patterns means that the research literature provides guidance on what patterns are necessary, sufficient, or probabilistically useful for inferring unobserved aspects of objects and events.

Successful inferences about Earth often require reasoning about a complex system that includes resource sinks and both negative and positive feedback loops. This reasoning, referred to as systems thinking, is poorly understood. Education to support systems thinking across the curriculum is critical, because the skill is required to understand the past and present and to make predictions about the future. Effective action on systemic challenges such as climate change requires deep understandings of nested and linked feedback loops.

Geoscience Illustrates the Value of Interdisciplinary Research That Integrates Natural and Social Sciences

A GER strength is the STEM-interdisciplinary-ness of geoscience. The geosciences draw on chemistry, physics, biology, and math to do our science; as such, geoscientists have learned to play well with others. GER has expanded the collaborative sphere to include the social sciences (e.g., education and cognitive psychology). A social science perspective on geoscience is critical to understanding the role of the mind in learning and disciplinary practice, the influence of emotions on learning in the field and classroom, and how to negotiate geosciences' role in important socioscientific issues (e.g., climate change, energy, and deep time). Thus, GER is well positioned by interdisciplinary experiences to engage in the convergence science at the human technology frontier (one of the NSF 10 big ideas) to further education and disciplinary practice. For example, there is an opportunity for developing a broad approach to science literacy that includes informal and formal learning throughout the life time. The geosciences have access to an unusual level of lifelong learning in the form of professional development (examples include the On the Cutting Edge Professional Development program and the InTeGrate program). These large-scale, center-based professional development projects were intentionally designed to support the complex system that is STEM education.

Geoscientists have articulated the value of, and how to effectively manage, large data sets. Educators are considering how to best support students in learning from big data. The geosciences, among other sciences, have a history of community management of big data in repositories, such as MinDat (a mineralogy database) and the Index to Marine and Lacustrine Geological Samples (a database that supports the Integrated Ocean Drilling Program and other ocean and lake coring datasets). This hard-won experience could accelerate development of data repositories that serve DBER-A. In science education, we already have a model in the Science Education Resource Center, which is managing all InTeGrate data, and in collaboration with NAGT could have the capacity to be a hub for hosting other large-scale datasets.

NEXT STEPS

Developing an effective transformation in science education requires a strategy in which theory and practice collaborate toward a common goal, recognizing practice as integral to the science. Peter Galison notes that in the history of science, significant progress often arises from efforts that require application of practice to concrete problems. Such work required experts from both theory and practice to meet in a common space—a trading zone. Such trading zones allow practical and theoretical progress in the absence of a Kuhnian revolution. GER is well positioned to take advantage of the power of such trading zones by already including both DBER and SoTL experts in its community. We suggest that overcoming the energetic barriers to collaboration across STEM fields will require building and extending our trading zones. Here, we offer three suggestions for kickstarting conversations in GER and across DBER-A on how to support constructing these relationships.

Look for Opportunities to Connect With Other STEM DBER People in Your Local Setting

A person-to-person connection may be the start of a collaboration and is a step toward reverse outreach to others around topics of interest or a local community of STEM education research and practice. We hope that this editorial, including Table I and the lists of research and practice benefits, may support starting conversations.

Form or Join Groups Affiliated With STEM-DBER-A Around Topics of Interest

Both DBER-A and GER will benefit from having GER represented by leaders and an organized presence as DBER-A develops. It was not coincidental that the May workshop was attended by two editors of *JGE,* an officer of NAGT, and an officer of the GER Division. Those institutions may want to consider formalizing that role as part of the job description or otherwise delegate individuals as the interface between GER and DBER-A. A natural set of trading zones will arise around questions that can best be answers by collaboration among experts across multiple DBER disciplines. At the moment, it is challenging for these people to find one another. Developing a database or other matching infrastructure will be an important tool for supporting these groups. A developing community of science educators and researchers within AAAS, called Trellis, is designed to support such efforts.

Consider the Key Goals and Concepts of GER in the Context of DBER-A

By adopting such a broad perspective, we may each subtly adjust our work for greater impact across STEM. If you have not already read "Towards the STEM DBER Alliance: Why We Need a Discipline-Based STEM Education Research Community" in the August issue of the *JGE,* we encourage you read it. As research progresses, the goals of DBER-A may not always overlap with the priorities of GER. Nonoverlap may reflect community-specific educational challenges or goals; however, it is worth considering how novel DBER-A goals might advance GER.

Wherever one's research passions lie, we suggest individuals can benefit from and can contribute to developing a more comprehensive approach to science education. We take the opportunity of this editorial to reiterate the importance of intellectually reaching out to build science person to person.

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