# Instructional Utility and Learning Efficacy of Common Active Learning Strategies

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## ABSTRACT
The adoption of active learning instructional practices in college science, technology, engineering, and mathematics (STEM) courses has been shown to result in improvements in student learning, contribute to increased retention rates, and reduce the achievement gap among different student populations. Descriptions of active learning strategies have been reported in other disciplines; however, the research literature that documents the success of these strategies may be unfamiliar to many geoscience instructors. This literature review seeks to serve as a bridge that connects the reflective practitioner, the research literature on instructional strategies, and the network of community resources available to the geoscience educator. We review the characteristics of 11 active learning strategies and weigh the evidence that these strategies improve student learning. Furthermore, we analyze the utility of these strategies in the context of their use in geoscience classrooms. We seek to provide geoscience instructors with a decision-making guide and evidence-based recommendations that they can use to select and implement active learning strategies that have the potential to enhance undergraduate learning experiences in geoscience courses. © *2017 National Association of Geoscience Teachers*. [DOI: 10.5408/17-249.1]

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## INTRODUCTION

Compared to other science, technology, engineering, and mathematics (STEM) fields that may be introduced to students during high school, the student experience in college-level introductory geoscience courses often serves as an entry point to attract students to the discipline (Levine et al., 2007; Houlton, 2010; Wilson, 2013). A student's experience in introductory courses represents a critical tipping point for persistence in STEM fields (Seymour and Hewitt, 1997). The adoption of empirically validated instructional practices has been shown to not only result in improvements in student learning (e.g., Pollock and Finkelstein, 2008; Derting and Ebert-May, 2010; Freeman et al., 2011, 2014) but also contribute to increased retention rates (Russell et al., 2007; Graham et al., 2013) and a reduction in the achievement gap among student populations (Haak et al., 2011; Eddy and Hogan, 2014). These teaching practices may extend beyond the classroom to include a variety of elements (e.g., course and curriculum design), but in the context of this review, we will examine instructional methods categorized as active learning strategies that can be deployed in typical college classroom settings. We define the characteristics of active learning in the section that follows. The summit on the Future of Undergraduate Geoscience Education (2014) noted that there is still limited adoption and faculty awareness of active learning pedagogies and encouraged the wider adoption of these practices. While the use of these teaching methods is becoming more prevalent in college geoscience courses (e.g., examples in Kober, 2015; compare Macdonald et al., 2005, and Manduca et al., 2017), many classrooms still rely almost exclusively on traditional lecture (e.g., Teasdale et al., 2017).

There remain some significant barriers to the more widespread use of active learning practices within the geosciences, even though the geoscience community has created an extensive collection of supportive educational resources (e.g., the Science Education Resource Center [SERC], http://serc.carleton.edu). Many descriptions of active learning strategies have been reported in other disciplines (e.g., Singer et al., 2012), but the research literature that documents the success of these strategies may be unfamiliar to most geoscience instructors. Even the most committed instructor would have to dedicate substantial effort over multiple semesters to find examples of suitable teaching activities, assess their utility for geoscience courses, and redesign relevant lessons. This preparation time, the time needed for instructors to develop materials and/or learn about effective teaching activities, represents a substantial barrier to sustainable reform (Henderson and Dancy, 2007, 2009; Henderson et al., 2011). This review seeks to serve as a bridge connecting the reflective practitioner, the literature on instructional strategies, and the network of community resources available to the geoscience educator. To achieve this goal and to help instructors overcome the barriers described above, we will do the following:

1. Review discipline-based education research (DBER) literature and summarize the evidence that specific active learning strategies support student learning.
2. Assess the strengths and limitations of the selected strategies on the basis of factors such as ease of implementation, availability of geoscience examples, and time commitment for preparation.

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3. Analyze the utility of these strategies in the context of their use in geoscience classrooms.

Where appropriate, we have included citations of accessible research articles from a variety of disciplines that can serve as an introduction to active learning for geoscience instructors. While several of these articles do not include geoscience examples, we have included links to examples of geoscience activities that use the same strategy in Supplemental Materials (available in the online journal and at http://dx.doi.org/10.5408/17-249s1). The result of this effort is to provide geoscience instructors with a decision-making guide and evidence-based recommendations that can be used to select and implement active learning strategies that have the potential to enhance student learning experiences in geoscience courses.

### What We Mean When We Talk About Active Learning

Just what is active learning, and what are the characteristics of strategies that are considered active? What do we look for in a strategy that would lead to a more active classroom environment? What do students need to do and think about to be active? Isn't note-taking an activity? To provide perspective toward answering these questions, we considered prior definitions and characterizations of active learning.

Bonwell and Eison (1991) defined active learning strategies as "instructional activities involving students in doing things and thinking about what they are doing" (p. 5). This definition was later expanded by Fink (2003) to delineate a "holistic view of active learning." (p. 105) that consisted of three primary components:

1. Communication of information and ideas largely that consists of students receiving content (via reading, direct instruction, etc.)
2. Experiences, divided into two types:
   a. "Doing" experiences, during which students participate and attempt the skill or activity we want them to learn (e.g., attempting to sketch a geologic cross section)
   b. "Observing" experiences, during which students observe something related to the topic they are learning about (e.g., video of a geological phenomenon)
3. Reflection, consisting of providing students with opportunities to reflect on their learning as individuals or in discussion with others

This inclusion of reflection-based activities as a component of active learning follows the example of Bransford et al. (2000), who included connections between learning environments and support of student metacognition within instructional activities. Metacognition, often simplified as "thinking about thinking" (Miller et al., 1970, 613), is a richly studied subdiscipline within educational psychology that examines how students evaluate and monitor their thinking during learning tasks (Flavell, 1971, 1973; Schraw, 1998).

Freeman et al. (2014) coded responses from 338 biology seminar participants and compiled a consensus definition of active learning as follows: "Active learning engages students in the process of learning through activities and/or discussion in class, as opposed to passively listening to an expert. It emphasizes higher-order thinking and often involves group work." (pp. 8,413–8,414). This was contrasted with traditional lecturing, which was considered "continuous exposition by the teacher" (p. 8,414). This definition of active learning within a STEM discipline contains many of the same components as the holistic active learning definitions described above (Bonwell and Eison, 1991; Fink, 2003). In addition, within DBER, Singer et al. (2012) acknowledged active learning's genesis in cognitive and educational psychology to provide a definition of active learning as a process that "requires students to select, organize, and integrate information, either independently or in groups" (p. 121).

Our working definition of active learning strategies combines the aspects of the definitions discussed above and includes one or more the following elements: (1) students participate in activities (either doing or observing) in addition to, or instead of, listening to direct instruction; (2) activities provide opportunities for student reflection on their learning or facilitate student–instructor interaction and assessment of learning; and (3) peer-to-peer interaction occurs as students complete the activity. While each strategy analyzed in this review may not inherently include all aspects of the three elements during its enactment, each provides a variable combination of two or more elements. We will provide information regarding which of the elements are present in each of the 11 active learning strategies discussed.

## METHODS

### Justification for Inclusion

All strategies included in this review were considered examples of active learning. Furthermore, the strategy has either been used in geoscience courses or is generally adaptable to geoscience teaching. Finally, the elements of the strategy are characterized sufficiently for practical implementation. Instructional strategies were excluded from consideration if the strategy: (1) was described so generally as to make it difficult to isolate applicable literature (e.g., discussion). (2) was either not studied enough or not studied sufficiently in isolation to have definitive evidence of its effectiveness (e.g., structured academic controversy), or (3) would primarily be used outside of class (e.g., peer review).

We began our review with a list of potential active learning strategies generated from an analysis of studies of DBER discussed in Freeman et al. (2014), a meta-analysis of pre-2010 research on the effects of active learning on student achievement and retention in undergraduate courses. We updated the Freeman et al. database by adding relevant post-2010 articles discovered using a Google Scholar search on specific active learning strategies, and we added some strategies that had been discussed almost exclusively in geoscience education research (GER). While our focus is on introductory geoscience courses, we drew examples from upper-level geoscience courses, other STEM disciplines, and occasionally social sciences and the humanities to present relevant research findings and a variety of descriptions of the use of each strategy.

Upon completion of this search and selection process, we identified 11 active learning strategies that were subsequently analyzed using two rubrics created to categorize and quantify the learning efficacy and utility of each

**TABLE I: Research validation rubric.**

| Efficacy | |
|---|---|
| Low | 1. Low strength of evidence (mostly practitioner wisdom or expert opinion), anecdotal or poorly constrained qualitative or quantitative data supporting the application of the strategy to improve student learning. |
| ↓ | 2. Low strength of evidence (mostly practitioner wisdom or expert opinion; may have some case or cohort studies), mixed results with learning gains in some settings but not in others OR of improved learning with infrequent application of strategy under review |
| | 3. Moderate strength of evidence (at least one case or cohort study conducted on the strategy), evidence of learning gains in one setting (classroom, field or lab) or inconsistent evidence of learning gains in two or more settings or disciplines |
| | 4. Moderate strength of evidence (at least one case or cohort study conducted on the strategy), consistent evidence of learning gains in two or more settings (classroom, field or lab) or disciplines |
| | 5. High strength of evidence (multiple cohort or higher level studies conducted on the strategy), evidence of consistent learning gains in one type of setting (classroom, field or lab) or inconsistent evidence of learning gains across two or more settings or disciplines. |
| High | 6. High strength of evidence (multiple cohort or higher level studies conducted on the strategy), consistent evidence of learning gains in two or more settings (classroom, field or lab) or disciplines |

strategy (see Supplemental Materials for discussion of how the rubrics were developed). These strategies are case studies and problem-based activities, concept maps, concept sketches, gallery walks, jigsaw activities, lecture tutorials, minute papers, peer instruction, role playing, teaching with models, and think–pair–share. More information about the creation and validation of the rubrics can be found in Supplemental Materials.

## Strategy Analysis

### *Learning Efficacy*

The learning efficacy category considers the robustness of the research evidence in favor of improved student performance as a result of the application of a particular teaching strategy. We considered the learning efficacy score using a six-point scale (Table I).

We classified the research articles for each strategy using a modified version of the GER Strength of Evidence pyramid (St. John and McNeal, 2017, this issue; see detailed discussion and Table S1 in Supplemental Materials). A third of the papers (32.8%) was coded as examples of either practitioner wisdom or expert opinion that described a teaching strategy without an associated assessment. The next largest group of papers was represented by case studies (29.7%) in which the author or authors analyzed data related to student learning associated with the application of a specific teaching strategy. An additional 13 papers (20.3%) were categorized as syntheses or meta-analyses assessing the impact of a strategy when used by multiple instructors. Cohort studies (12.5%), representing multiple iterations of a strategy by the same instructor, and systematic reviews (4.7%) were less common. Pedagogical research suggests that all strategies discussed herein exhibit features that should promote learning or otherwise improve the student experience. However, some strategies have more empirical evidence to validate their use as aids in promoting student learning. Table I serves as a holistic ranking of the research support for a strategy as a combination of the strength of evidence available in the peer-reviewed literature and the direction of that evidence (positive, negative, or neutral).

### *Utility*

Each strategy was reviewed against a common set of instructional criteria divided among three categories (preclass preparation, student strategy use, and task characteristics; Table II), which combined to represent the utility of the strategy (following the example of Dunlosky et al., 2013). The first category contains three criteria that relate to the level of preclass preparation required of the instructor to implement the strategy, including preparation time, resources required, and availability of adaptable examples (see summary in Table II). The rating for instructor preparation time was based on estimated time to create an activity from scratch or adapt from existing resources, as opposed to using an already-available activity. The second category contains criteria that relate to in-class use of the strategy, specifically how readily students could complete the activity (how much explanation is required), the level of student–student interactivity it fosters, and how readily the instructor can assess student learning during or after the activity (Table II). The third category relates to application characteristics of the specific strategies, which include how much class time it takes to employ the strategy, potential class size limitations, and how frequently an instructor would be able to effectively employ the strategy. Each strategy was assigned a utility score of one (low utility), two (moderate utility), or three (high utility) for each of nine criteria (Table II). Strategies that have a high utility have a number of features that make them more straightforward to use. For example, they can be easily prepared, examples are readily available, and they can be used frequently during a lesson in any size of classroom. Strategies with moderate or low utility require more time investment for teacher preparation and assessment and would likely not be used as often or as readily in larger

TABLE II: Strategy utility rubric.

| Rubric Category/Criteria | Low Utility (1) | Moderate Utility (2) | High Utility (3) |
|---|---|---|---|
| **Preclass Preparation** | | | |
| Instructor preparation time | Significant prep time (>60 minutes per class) | Moderate prep time (15–60 minutes per class) | Minimal prep time (<15 minutes per class) |
| Required resources | Physical materials and/or technology needed for all students or small groups | Some materials and/or technology needed | No resources or few resources (e.g., paper handouts) required |
| Availability of examples | No or few sample activities available for instructors | Some sample activities available but not representative of all aspects of course | Plentiful supply of sample activities covering all course content freely available for instructors |
| **Student Strategy Use** | | | |
| Ease of student use | Student use requires significant direction and/or training for each iteration of activity | Student use requires either initial training phase or some activity setup for each iteration | Student use is intuitive, involves few steps, and requires minimal direction after first few iterations |
| Student–student interaction | Standard format involves students individually completing activity | Activity involves some student–student work or depends on instructor use | Activity requires students to work together for duration |
| Assessment ease | Instructor assessment of student learning requires time-intensive postclass review of student work products or is not possible | Instructor assessment of student learning can be completed quickly with postclass review of student work products | Instructor can quickly qualitatively or quantitatively assess student learning during class |
| **Task Characteristics** | | | |
| Class time | Use of strategy takes most of class period or longer (e.g., one class meeting of ~50 minutes) | Use of strategy takes ~10–30 minutes per assignment | Use of strategy takes a few minutes or less per assignment |
| Class size restrictions | Strategy would be difficult to apply consistently in medium to large classes (>30 students) | Strategy would be difficult to apply in large classes (>70 students) | Strategy can be readily applied in classes of all sizes |
| Potential use frequency | Strategy can be applied no more than a few times per semester | Strategy can be applied once per class | Strategy can be readily applied up to several times per class |

classes. (See Supplemental Materials for a thorough description of how the rubric was developed and applied.)

### Review Structure

What follows is the result of our analysis in applying the rubrics described above (also see Supplemental Materials) against the 11 strategies listed previously. Each description includes a brief synopsis of the active learning strategy, a discussion of why we consider it active learning, the evidence of its effectiveness, and notes regarding its preparation, implementation, and assessment. We seek to provide information to instructors who can then assess the value of incorporating each active learning strategy into their classes. The highest-scoring strategies have the greatest utility, with robust effects and the potential to be adopted widely. Lower-utility strategies have effects that are less generalizable and/or may hold promise but have insufficient evidence of a positive impact on student performance.

The description of the strategies is presented in alphabetical order. The reviews are modular so that discussions of each strategy can be reviewed independently and common factors can be readily compared among strategies. Finally, for each strategy, we discuss issues with implementing the technique and present specific geoscience examples that can be adopted by instructors or serve as samples of how one might use the strategy in a geoscience context. A compendium of links to ready-to-use activities associated with each strategy is provided in Supplemental Materials.

## ACTIVE LEARNING STRATEGY REVIEW

### Case Studies and Problem-Based Activities

*Description*

"Problem solving" is an umbrella term that has different meanings and implications depending on its context (Barrows, 1986). This variation influences its effectiveness and the level of higher-order thinking skills involved. Several specific strategies incorporate the use of problem solving into their methodology, such as problem-based learning (PBL; Wood, 2003); investigative case-based learning (Waterman, 1998); process-oriented, guided-inquiry learning (POGIL; Hanson, 2006); and case studies (Herreid, 1994). The context provided for a problem is often considered the "case." We consider case studies and problem-based activities together, because they share several characteristics. Case studies are essentially stories that present realistic, complex, and contextually rich situations and often involve a dilemma, conflict, or problem (Herreid, 1997–1998). Case studies feature some combination of the following characteristics: the event occurred relatively recently, the reader feels empathy for the characters involved, and the case presents a topic relevant to the reader (Herreid, 1997–1998). For example, a PBL example (Stormy Weather; see Supplemental Materials for details) guides students through a series of steps over two lab meetings to predict changes to the weather in multiple locations and then to evaluate the success of their predictions. A case study example (The Slippery Slope of Litigating Geologic Hazards; see Supplemental Materials) could generally be completed in a single class meeting. The case examines a landslide hazard and is divided into three parts that each involve students reviewing 1–2 pages of text and figures and responding to some related questions. Methods such as PBL, POGIL, and investigative case-based learning may require the use of multiple class periods, independent student work outside of class, and close interaction between small groups of students and the instructor (Wood, 2003).

### How It Is Active

Case studies and problem-based activities present students with opportunities to participate in authentic experiences and often include significant peer-to-peer interactions to solve problems. They are generally low in reflection opportunities and do not automatically increase student–instructor communication.

### Research Validation

Problem-solving techniques are used across the curriculum, from K–12 (e.g., Chang, 2001; Birnbaum, 2004) to college (e.g., Lev, 2004; Riggs et al., 2009), with little evidence of their success in introductory Earth Science classrooms. When they have been applied in college geoscience courses, it is typically in upper-level classes. For example, Lev (2004) used a PBL exercise as a capstone experience in a 300-level environmental geology course. Over 3 weeks, students were asked to analyze a made-up facility site and apply their knowledge of environmental laws, chemical contaminants, risks associated with contamination levels, hydrogeology, and remediation techniques. Most students responded positively to the exercise, though some struggled with the lack of explicit outcomes (Lev, 2004). Riggs et al. (2009) used a problem-solving approach in an advanced field geology course for undergraduate geology majors as part of a larger study analyzing students' navigational choices in the field. Goldsmith (2011) applied a case-based approach to the redesign of the curriculum of an introductory geology course and demonstrated an improvement in students' learning and their ability to engage in higher-order thinking (e.g., analysis, synthesis, and evaluation) about the subject matter. However, although he redesigned his approach to the course around six overarching questions, he continued to use a traditional lecture format (i.e., little active learning) for the class (Goldsmith, 2011). In other disciplines, research findings have often focused on the development of higher-order thinking skills associated with the implementation of PBL or case studies (e.g., Dinan, 2002; Anderson et al., 2008). Dochy et al.'s (2003) meta-analysis of 43 PBL studies reported a consistent positive signal of improving student skills (application of knowledge) but produced a negative, though not practically significant, result for increasing student knowledge (facts and concepts) in comparison to traditional instruction. However, a more recent meta-analysis by Walker and Leary (2009) that reviewed a variety of PBL implementations and disciplines demonstrated that students using PBL often outperform students in lecture-based courses, especially outside the discipline of the medical education.

### Preclass Preparation

Case studies and problem-solving activities involve the instructor providing students with a real-world or simulated situation that requires them to apply what they know to address an issue. The development of such scenarios takes considerable time and effort unless appropriate resources exist with adaptable examples. Preparation involves reviewing the details of a problem or case and preparing student handouts and related worksheets. Instructors should consider student demographics and what might enhance the discussion based on students' backgrounds and prior experiences. Limitations to using this approach include the time necessary to find, or to develop, an appropriate scenario with supporting resources. The National Center for Case Study Teaching in Science (NCCSTS, http://sciencecases.lib.buffalo.edu/cs/collection/) is the source of the landslide case described above and includes links to more than 600 other cases, with several characterized as suitable for lower-level undergraduate classes involving Earth Science (26 examples), environmental science (104), geology (13), geography (8), or paleontology (9). Each case includes a relatively brief story description and a series of related questions that can be presented by the instructor. A variety of problems are available through the PBL Clearinghouse at the University of Delaware (http://www1.udel.edu/inst/), but relatively few problems feature environmental (3 examples) or geoscience (3) themes.

### Student Strategy Use

Case studies and problem solving typically require students to read and interpret text and/or data and collaborate to generate an answer. During these interactions, students are asked to establish multiple working hypotheses, collect or evaluate data, and determine a course of action, thus allowing students to become more active participants in the "doing" of science. This can be effective if students are well versed in such interactions, but instructors may face resistance unless students recognize that these activities are related to their course assessment (Herreid, 2001). Small groups of students can work collaboratively to answer the questions and to contribute to the whole-class discussions. This approach may involve student work outside of the classroom, for example, as participants in a preclass reading assignment or as independent researchers between classes. Instructor assessment of student work may range from commenting on a selection of verbal reports during class to scoring of individual writing products as assigned homework. The former has the potential to be completed relatively quickly, whereas the latter may be time consuming and challenging, especially in large classes.

### Task Characteristics

An instructor might use problem solving or case studies to illustrate and enrich lecture material. These activities are typically regarded as class-length activities (see Supplemen-

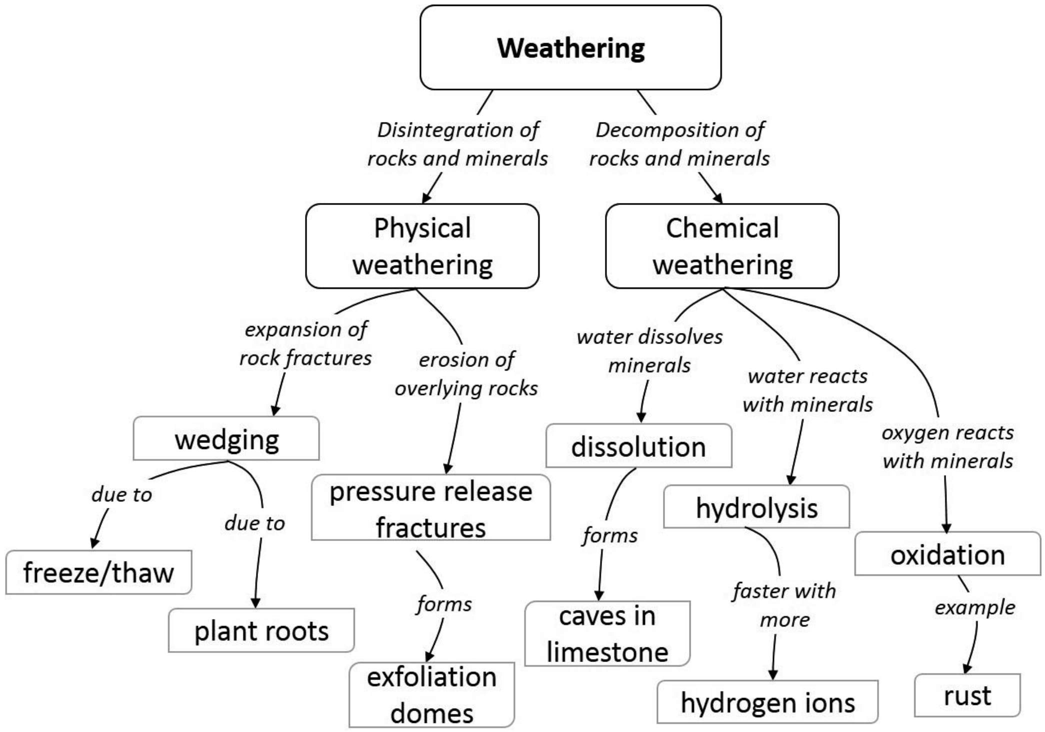


**FIGURE 1: Example of a concept map for weathering.**

tal Materials) or may represent capstone exercises that involve several weeks of student work (Lev, 2004). Instructors can shorten the duration by having students complete necessary readings prior to class. While strategies such as PBL and POGIL were developed for smaller, seminar-style teaching environments, these types of activities can be adapted for use independent of class size as long as the instructor can provide the necessary teaching materials (e.g., handouts and worksheets) and support for groups of students in larger classes. Given the degree of effort required, these types of activities are more likely to be used infrequently in geoscience classrooms that are choosing to target higher-order thinking skills.

### *Summary*

We categorize case studies and problem-based activities as active learning strategies with moderate utility and high learning efficacy (Tables I and II). These strategies have the potential to be effective in promoting student learning but require significant effort in some aspects of their development, deployment, and assessment. Research has not addressed the use of these strategy in introductory geoscience classes. There is some evidence that the guided discussion that takes place during these activities can improve student communication skills and promote engagement, but there is mixed evidence that the strategies enhance student knowledge of course content or concepts.

## Concept Maps

### *Description*

Concept maps are graphical representations of one's knowledge of a topic that stress the similarities and connections among various ideas and concepts (Novak and Gowin, 1984; Novak, 1990; Novak and Cañas, 2008). Concepts are usually drawn within a circle or box and are connected with labeled arrows or lines that indicate how they relate (e.g., Fig. 1). McConnell et al. (2003) and Quinn et al. (2003) discuss the use of concept maps in introductory geoscience courses. Concept maps can be simple, with a few concepts and connections, or highly complex, with many cross connections among numerous concepts. Concept maps represent a versatile strategy that can be used in a variety of ways to explore student learning. For example, an instructor may address knowledge and comprehension by having students fill in of a partially completed concept map (Ruiz-Primo et al., 2001). Alternatively, students may be asked to analyze several student-generated concept maps and discuss which best represents information presented in class. The generation of original concept maps requires students to organize their ideas and graphically synthesize concepts. Having students complete, generate, and/or evaluate concept maps provides opportunities for peer discussions, instructor modeling of thinking processes, and in-class feedback on learning. Many studies have examined the use of concept maps as objects created by individual students at the conclusion of a lesson (e.g., Ruiz-Primo et al., 2001; Quinn et al., 2003), but Hay et al. (2008) and Kinchin and Hay (2005) discuss the group construction of concept maps. We include this latter format here as an example of active learning.

### *How It Is Active*

Concept maps provide students with an opportunity to commit their thinking to paper. The construction of a concept map (depending on the level of scaffolding provided) can provide opportunities for experiences and reflection. If concept maps are completed in pairs or groups, they can generate significant peer-to-peer interaction.

*Research Validation*

Nesbit and Adesope (2006) conducted a meta-analysis of 55 studies that examined the effects of concept mapping across a range of disciplines and student age groups and concluded that the use of concept maps enhanced knowledge retention when compared to reading, traditional lecture, or class discussion. They also found that the strategy is slightly more effective in terms of knowledge retention than writing summaries or outlines (Nesbit and Adesope, 2006). Ruiz-Primo et al. (2001) reported that some concept map formats (construct a map from scratch) were more effective than others (fill in the map) in identifying gaps in student knowledge. Quinn et al. (2003) analyzed a series of three concept maps generated at different times over a semester by 61 students in an introductory geology course and found that they illustrated an increasingly sophisticated understanding of course content that reflected a restructuring of student knowledge around critical concepts as the semester progressed. In contrast, Englebrecht et al. (2005) had more than 3,000 students use concept maps to illustrate increasing content knowledge in a two-semester physical geology sequence. Although the concept maps became progressively larger and demonstrated an increase in knowledge, Englebrecht et al. (2005) noted that the knowledge was poorly integrated, with relatively few links between new information and previous knowledge. Clark and James (2004) described the use of concept maps in designing the sequence of lessons for a structural geology course but didn't report using them as a class activity. Daley and Torre (2010) reviewed the use of concept maps in medical education and noted that this strategy fostered critical thinking and problem solving (e.g., Torre et al., 2007; Gonzalez et al., 2008). Karpicke and Blunt (2011) reported that retrieval practice may be a more effective learning technique than concept mapping under their test conditions, but Mintzes et al. (2011) suggested that this could be due to a lack of student training in the use of concept mapping.

*Preclass Preparation*

Depending upon how the instructor plans to use concept maps, they may require minimal to modest preparation and resources. Instructors may need to do little more than identify a suitable topic and set aside sufficient time for students to complete an original concept map. In contrast, there are few examples of fill-in-the-blank–style concept maps that are premade and ready for use in geoscience courses and relatively few examples of geoscience concept map activities suitable for introductory courses (see Supplemental Materials).

*Student Strategy Use*

Students who have not encountered concept maps in high school may need to gain some experience in using concept maps. Instructors may begin this process by providing copies of skeleton maps (an expert map with blank spaces for missing terms and a list of potential terms) or partially completed maps for student practice (e.g., Ruiz-Primo et al., 2001). Quinn et al. (2003) and Englebrecht et al. (2005) discuss the need to train students in generating concept maps early in the course. Concept mapping can be a valuable tool in the geoscience classroom for tasks requiring synthesis of concepts or when there is an emphasis on systems thinking. Generating a concept map requires significant communication within student groups, including listening to and interpreting the ideas of peers. Concept maps provide an opportunity for formative assessment of student work to identify gaps in comprehension. Ruiz-Primo et al. (2001) reported that it was easier to grade student work and the students typically scored higher if assessments involved them filling in partially completed concept maps rather than creating their own. While some have applied multipart grading schemes to score student-generated concept maps (Ruiz-Primo and Shavelson, 1996; Quinn et al., 2003), it may be more straightforward for instructors to generate simple rubrics that allow them to divide concept maps into one of three categories (e.g., poor, fair, or good) if grading is required. Alternatively, the structure of concept maps, ranging from simple linear plots to sophisticated network maps, can serve as a proxy of their cognitive sophistication (Kinchin et al., 2000; Yin et al., 2005).

*Task Characteristics*

Concept maps involving synthesis may be most applicable as a formative or summative capstone exercise toward the conclusion of a lesson or chapter, because they require students gain a suite of knowledge on a topic before they can explore the connections through concept mapping. In contrast, skeleton (fill in the blank) maps may provide an opportunity for formative assessment activities that break up a lecture and allow the instructor and students to resolve misunderstandings. Depending on the depth of content and number of concepts to be included, creation of even the simplest concept map may take at least 10 minutes and often longer. Hay et al. (2008) contended that most students can complete a reasonable concept map in 20–30 minutes. Because the generation of a concept map requires little more than a piece of paper and a pencil, these activities can be carried out by small groups of students in classes of almost any size.

*Summary*

We categorize concept maps as a strategy with moderate utility and high learning efficacy. The versatility of this strategy to address both lower- and higher-learning skills with a single approach makes it adaptable to use with almost any content in relatively brief assignments that test knowledge or comprehension or for more rigorous assessments targeting analysis and synthesis. While concept maps can be generated with little more than a pencil and paper, the availability of free software to create concept maps on a variety of platforms (see Supplemental Materials) may make these assessments more accessible for use as homework or lab activities. While there is limited evidence of improved learning within the geosciences, the use of concept maps has been shown to produce significant improvements in student performance in multiple disciplines and settings.

## Concept Sketches

*Description*

A concept sketch illustrates the main aspects of a concept or system, annotated with concise but complete labels. These labels may (1) identify features, (2) depict processes, and (3) characterize the relationships between features and processes (Johnson and Reynolds, 2005). In the geosciences, concept sketches are often simplified cross sections but can include map views or perspective views. Johnson and Reynolds (2005) outlined one approach to using concept sketches in a lesson on plate tectonics: (1) Students begin with an exploration phase by viewing a short animation depicting the evolution of a plate boundary; (2) students are asked to observe the processes and write a list of essential elements to include in their concept sketches; (3) students participate in think–pair–share (Lyman, 1987; Macdonald and Korinek, 1995), during which they compare observations with their peers; and (4) different groups contribute their observations to a global list to be shared with the class.

The instructor may then guide a whole-class discussion to identify which topics seem most important to include in the concept sketch, or student groups may negotiate this among themselves. These discussions provide an opportunity to introduce terms and concepts associated with the plate boundary (e.g., subduction and causes of melting). The final list of observations provides a starting point for student concept sketches, which can be generated on a portable whiteboard, large sheet of paper, or in student notebooks. Students then explain their sketches to neighboring classmates or to other groups; some may present their sketches to the class by way of a mini-presentation, or their sketches can be used as formative assessments (Johnson and Reynolds, 2005).

### How It Is Active

Concept sketches require students to contend with their internal conceptualizations and spatial orientations of phenomena. They provide students opportunities for both doing (via a student's own attempt at a sketch) and observing (via an instructor's example) experiences. However, they are low in the reflection element and do not necessarily increase peer-to-peer interaction unless completed in groups. They can increase student–instructor communication if student samples are analyzed by the instructor.

### Research Validation

The value of student-generated sketches has been demonstrated by several studies (e.g., Schwartz, 1993; Cox, 1999), including one focused on plate tectonics (Gobert and Clement, 1999; see also Gobert, 1997). Gobert and Clement (1999) found that middle school students who sketched as they read outperformed students who wrote summaries or students who simply read the text. In addition, Johnson and Reynolds (2005) reported that students who either sketched or wrote explanations as they read were better able to explain the processes, whereas students who wrote summaries tended to have somewhat listlike recall of the material but not a good working knowledge. Lastly, concept sketching encourages student discussion and small-group learning, which have been shown convincingly to improve student learning and attitudes (Springer et al., 1999). Although no studies directly compared student learning in equivalent settings with and without the use of concept sketches, numerous studies have demonstrated greater learning when text and figure are combined rather than presented separately (e.g., Mayer, 2001).

### Preclass Preparation

Concept sketches can be used in a variety of class settings, and instructors already generate concept sketches during lessons to demonstrate how to organize and explain knowledge. Students can generate concept sketches in their notebooks without the need for specialized resources or instructors may prefer to provide whiteboards or other materials that make it easier to share illustrations. Prompting material (e.g., photographs and in-class demonstrations) used to help create concept sketches can be provided in any class size and may already be present in the presentations of most instructors. For instance, several examples of a geological feature, such as photographs of different unconformities, are shown to students, and then the students generalize these examples into a typical unconformity concept sketch. Short video clips have the ability to show motion and changes over time and represent ideal prompts because they can show visually active processes, such as volcanic eruptions or destructive weather. Johnson and Reynolds (2005) showed video clips of many styles of volcanic eruptions, introduced appropriate terms (e.g., pyroclastic flow), and asked students to construct a concept sketch for that type of eruption.

### Student Strategy Use

Sketching is something that almost every student could potentially do in class daily. Students need minimal guidance in creating a concept sketch, especially if the instructor has modeled generating sketches as a component of their instruction. Generating concept sketches and explaining them to their neighbors provide students with the opportunity for peer interaction that helps them process course information more fully, consolidate their understanding, and personalize the information to suit their learning needs. Review of concept sketches provides instructors with an opportunity to identify student misconceptions. Even in a large class, the most common errors will likely reveal themselves after review of a representative sample of sketches. Consequently, a concept sketch exercise may represent an excellent formative assessment to be used to provide feedback to the class. An instructor who chooses to grade these materials as part of a summative assessment may reduce the time required by applying a general rubric (see Johnson and Reynolds, 2005).

### Task Characteristics

The initial generation of a concept sketch, subsequent discussion and/or comparison with peers, and instructor discussion of the ideal set of features is likely to take at least 15 minutes, depending upon the complexity of the illustration (Johnson and Reynolds, 2005). Tasks that involved generating concept sketches following the use of paper maps, the manipulation of hand specimens, and student participation in experiments may be more readily administered in smaller classes and labs. Students will complete their sketches at different rates; consequently, although there may be no restriction to the size of class, instructors in large classes may face challenges in keeping student attention focused on the task at hand (Johnson and Reynolds, 2005).

### Summary

We categorize concept sketches as a strategy with moderate utility and low learning efficacy. Two of the principal values of this strategy are that it is straightforward to implement in almost any setting and it replicates a strategy that can be readily modeled by the instructor. There is little published evidence of improved learning among the geosciences when using concept sketches as an active learning strategy, but the use of labeled sketches has been shown to produce improvements in student learning in several educational settings.

## Gallery Walks

### Description

This active learning strategy is analogous to walking through a gallery to view works of art, except that this strategy requires viewers to record an explicit response to each piece. A gallery walk begins with the instructor creating a series of questions or prompts and posting them at stations around a room (Fasse and Kolodner, 2000; Francek, 2006). This is typically done using questions written on large sheets of paper or whiteboards. A gallery walk is a small-group assignment that requires students to rotate from station to station and provide responses to the questions or prompts. Each group begins the assignment at a different station and provides an initial response to a prompt or question. Next, the groups move to other poster stations and add comments and ideas to responses provided by the initial group. Groups rotate through all posters until they return to their starting point. Finally, following time for group reflection, the materials on each poster are summarized for the rest of the class and may be used for further discussion guided by the instructor (Francek, 2006).

Gallery walks can be used to have students explore what they know about a topic, assess student understanding of an assignment, introduce new information, or provide exam review. An exploration-type activity by Edwards (2017) has students brainstorm responses to prompts related to climate change (e.g., potential poster prompts include natural causes, role of the individual, and scientific factors) for 15 minutes at the beginning of class. The first unit of the InTeGrate Climate of Change module (Shellito, Walker, and Fadem, 2016) includes a 15- to 20-minute gallery walk that has students respond to six questions and prompts related to a preclass reading assignment (e.g., the climate of a particular place on Earth can be affected by…).

A gallery walk may be used as an exploration activity to examine students' preexisting knowledge at the start of a lesson, or it may be used to provide a physical and mental break in lecture for which the instructor designs the sequence of questions or prompts to scaffold the presentation of key course concepts. This strategy involves students working collaboratively to respond to challenging questions using higher-order thinking skills and provides opportunities to develop communication skills. However, a gallery walk may present challenges in the scale of execution for larger classes.

### How It Is Active

Gallery walks are inherently rich in each of the three primary elements of holistic active learning. These activities provide students with experiences (doing and observing), as well as occasions for reflection during the analysis of their own and other groups' responses to instructor prompts. Furthermore, gallery walks are collaborative by design, thus increasing peer-to-peer interaction in the classroom.

### Research Validation

Research on active learning may include gallery walks among several types of class activities (Kolodner, 2004), thus making it difficult to separate out their effect on learning. Alternatively, the use of gallery walks may be presented as a form of practitioner wisdom (Kolodner and Nagel, 1999; Fasse and Kolodner, 2000; Francek, 2006). While a gallery walk provides an opportunity to learn what students know about a topic and about their misconceptions, there is little research on whether this strategy results in improved learning in comparison to traditional lecture. Gallery walks (runs) were used in a small introductory geomicrobiology course (Hernández-Machado and Casillas-Martínez, 2009) and were effective at promoting student participation and discussion and resulted in better group-generated question responses compared to individual students' quiz responses.

### Preclass Preparation

Prior to class, an instructor must generate questions or prompts and write them at the top of several blank posters or whiteboards. While there are some examples of these activities for specific situations, it may take time to generate an appropriate series of questions that will provide a consistent challenge to participating students. Depending on the topic and size of class, four to six posters may be used. Once the questions or prompts have been designed, minimal instructor preparation may be required beyond supplying paper and pens.

### Student Strategy Use

Small teams (five or fewer students) generate a response to the prompt or question provided, typically by writing or drawing on the poster. This is a relatively straightforward task for most students and provides an opportunity for significant interaction to generate answers. Instructors may be challenged to have students provide more than perfunctory answers and to ensure that all group members contribute fully (Francek, 2006). Instructors can encourage student participation by circulating among stations and asking probing questions. Gallery walks provide a product that contains contributions from members of all participating student teams. The completed posters represent a snapshot of how the class views a topic. The instructor may choose to use the gallery walk products as a low-stakes or no-stakes formative assessment of each group.

### Task Characteristics

Depending on the number and sophistication of tasks, the time necessary for individual gallery walks can vary from 15 minutes to whole class periods. Gallery walks are more difficult to implement and manage in large classes. In a large class, multiple sets of posters with the same prompts may be provided to allow for a greater number of groups. Because of the time and organization involved, gallery walks may be used less frequently in comparison to some other active learning strategies.

### Summary

We categorize gallery walks as a strategy with moderate utility and low learning efficacy. This strategy introduces a physical activity in class that may be a welcome change to sedentary students, and it has the potential to promote discussion and foster peer interaction. The principal challenges come from generating a suitable suite of poster topics, implementing this strategy in even moderately sized classes, and having a true assessment of student knowledge. There is almost no published evidence of improved learning in any college setting when using gallery walks.

## Jigsaw Activities

### *Description*

A jigsaw activity is a collaborative learning technique that tasks individual students with becoming experts on certain information that they then share with other expert peers in a group to build a deeper conceptual understanding (Aronson et al., 1978). Tewksbury (1995) provided detailed instructions about using jigsaw activities in class. An instructor first has students form small expert groups in which all students in each group review the same material. These students discuss the materials and arrive at a common understanding through peer teaching. Next, students are reorganized into new groups in which each group member brings a different expertise. This new group applies their combined expertise to complete a task in response to an instructor's prompt or question. For example, Sawyer et al. (2005) has students discover plate boundaries as an introductory inquiry exercise in learning about plate tectonics. Students are divided into four discipline groups in which they examine maps illustrating worldwide earthquake distributions (seismology), active volcano locations (volcanology), age of the seafloor (geochronology), and distribution of landmass and elevation (geography). They work in their specialist groups to identify patterns and potential boundaries between plates. After coming to a consensus on their self-identified boundary types, they rearrange into new groups consisting of one student expert from each discipline. In this second arrangement, students explain their boundary types to their peers using supporting evidence from their discipline-specific dataset. Student groups then combine their expertise and data to generate a unified set of boundary types referencing all geophysical datasets (Sawyer et al., 2005). These boundaries are then presented to the class at large and compared to other groups. After these group presentations, the instructor can confirm, edit, and support areas of the students' arguments and provide supplemental information relating to the accepted plate boundary types. Dunn et al. (2016a, 2016b) developed jigsaw activities on Earth's radiation budget and atmospheric circulation modeled after the format of the Sawyer et al. (2005) activity.

### *How It Is Active*

Jigsaw activities provide authentic experiences for students during their expert phases, when students participate in doing experiences, collecting and synthesizing information for distribution to the larger group. These types of activities are also designed to increase peer-to-peer interaction. Reflection opportunities for jigsaw activities are generally low unless added as a follow-up activity.

### *Research Validation*

When experimentally compared to more traditional teaching of similar topics in college settings, jigsaw activities have elicited mixed results. This has previously been partially attributed to poorly constrained experimental designs and unequal comparison populations in many of these studies (Moskowitz et al., 1985). Some studies investigating jigsaw activities and their effects on student learning have shown no difference in student performance (Palmer and Johnson, 1989), while others have been found learning gains in an introductory chemistry course (Doymus, 2008) and in a high school humanities course (Göçer, 2010). The use of jigsaw activities in the geosciences has been described by several authors (Tewksbury, 1995; Sawyer et al., 2005; Grissom et al., 2015), and the strategy has been applied in other disciplines, receiving positive reviews from students but providing little direct evidence of improvements in learning (Colosi and Zales, 1998; Burkhardt and Turner, 2001; Perkins and Saris, 2001). Examples of geoscience jigsaw exercises are available in online repositories (see Supplemental Materials).

### *Preclass Preparation*

A moderate amount of preparation must be undertaken to create or adapt a jigsaw activity for use in class to (1) match the learning objectives of the activity with the content, (2) determine meaningful divisions of content to make each student's piece of the puzzle an important contribution to the whole, (3) design a final culminating activity that requires input from all team members, and (4) plan the procedural aspects of the activity, including how, when, and where students will move between their home and their expert groups. To manage a jigsaw activity, an instructor needs to prepare copies of separate pieces of information for each group member and budget sufficient time to conduct the activity. Some of the activity may be presented as a preclass assignment to save time in class (e.g., Colosi and Zales, 1998; Doymus, 2008). (See Supplemental Materials for examples of jigsaw activities on topics such as plate tectonics, mineral identification, and volcanoes.)

### *Student Strategy Use*

Students begin the activity by working with peers on a common topic or reading; consequently, student participation is relatively intuitive. Jigsaw activities have the potential to create an engaging classroom environment that gives each student a significant role in the collaborative learning process. These activities promote peer teaching and increase the level of accountability for individual students, because every student must participate for the group to successfully complete the culminating task. A successful jigsaw activity should result in peer-to-peer interaction throughout the exercise. Summative assessments of sophisticated jigsaw activities, like the discovering plate boundaries exercise described above, may be time intensive, but instructors may choose to use such activities for a formative assessment in class. Such tasks provide students with a common source of information that can form the basis for subsequent summative assessment questions.

### *Task Characteristics*

Jigsaw activities can be added to any classroom setting or size, although the process of reorganizing students into expert groups presents a greater challenge in large classes. The instructor may choose to distribute group materials before class to minimize class time dedicated to the activity. Given the two-part group activity and subsequent group and/or whole-class discussion, a jigsaw activity is likely to occupy a significant portion of class time. Colosi and Zales (1998) identified 10–40 minutes for jigsaw groups.

### *Summary*

We categorize jigsaw activities as a strategy with moderate utility and moderate learning efficacy. Jigsaws have the benefit of increasing student engagement around well-designed activities, several of which are already available online. Furthermore, there are several published examples of the use of this technique in a variety of settings from classroom to lab to guide instructors in its use. Unfortunately, few of these studies examined the effects of the deployment of this strategy on student learning; consequently, we have little evidence in terms of substantiating the learning efficacy of jigsaw activities.

## Lecture Tutorials

### *Description*

Lecture tutorials include structured prompts to which students provide written feedback. These activities are designed to target misconceptions and conceptually challenging content and may include figures or tables in questions created to have students participate in critical reasoning tasks (Prather et al., 2004; Kortz et al., 2008). Prather et al. (2004) describe a three-step process for lecture tutorials: (1) The instructor presents an abbreviated lecture on a specific concept, (2) students collaborate to answer a series of questions and are guided through this process by the instructor and learning assistants (if available), and (3) the instructor debriefs the class and reviews the questions to explain the reasoning behind optimal answers.

### *How It Is Active*

Lecture tutorials provide students opportunities for relatively straightforward doing experiences that are built around peer-to-peer and student–instructor interactions. They do not necessarily provide students opportunities for reflecting on their knowledge or process of learning.

### *Research Validation*

A tutorial approach to student learning has had success in physics (McDermott and Shaffer, 1998) and has been adapted to fit a lecture setting in astronomy (Prather et al., 2004; Wallace et al., 2012) and geology (Kortz et al., 2008). Kortz et al. (2008) found that students using lecture tutorials in introductory geoscience courses were able to outperform peers who only had the lecture on related multiple-choice exam questions. Prather et al. (2004) reported a similar effect in an astronomy course for nonscience majors, but in subsequent studies, he and his colleagues noted that learning gains were dependent upon how the instructor implemented the strategy (Wallace et al., 2012).

### *Preclass Preparation*

Lecture tutorials do not require specialized equipment beyond a multipage student handout. Preparation time for the instructor is variable. Creating a handout requires the instructor to first identify the misconceptions to address and create related questions, including related images or data. Sample geology lecture tutorials are available online (see Supplemental Materials) or in published collections (Kortz and Smay, 2012).

### *Student Strategy Use*

Lecture tutorials are relatively straightforward. They typically include a list of questions to be answered following part of a lesson. Students may be required to select multiple-choice answers or compose short written responses. Researchers suggest that these materials be used formatively, without an associated grade (Wallace et al., 2012); consequently, class size isn't a limiting factor. Because student responses follow a prescriptive format, worksheets can be used to check for accuracy, even having students trade and grade each other's work. The instructor can use feedback from students at the conclusion of the task to determine whether sufficient learning has occurred and to correct remaining misconceptions. Students leave the class with completed activities that can be used to study for upcoming exams.

### *Task Characteristics*

Lecture tutorials have been applied in large classes (Prather et al., 2004), with the only restriction being the instructor's ability to print the necessary handouts. The time students spend on a worksheet can range from less than 5 minutes to an entire class period, though 10–20 minutes is typical (Kortz et al., 2008). It is likely that instructors would deploy a single lecture tutorial per class due to the time commitment necessary.

### *Summary*

Lecture tutorials are relatively quick to assemble, provide students with additional practice and confidence, and can be used as informal assessments of learning. Furthermore, researchers in two disciplines have found significant learning gains when they incorporated lecture tutorials into their classes. We consider this strategy to have a moderate classroom utility and high learning efficacy.

## Minute Papers

### *Description*

Minute papers (also called 1-minute essays) are brief, flexible exercises during which students have an opportunity to reflect on and write about course content (Weaver and Cortell, 1985; Wilson, 1986; Angelo and Cross, 1993). Short, often anonymous, written responses to instructor-generated prompts can relate to course concepts that either have been recently covered (as a form of formative assessment) or are soon-to-be covered (as a way to activate prior knowledge or explore preconceptions). These responses are then collected by the instructor and reviewed either in total or via a representative randomly selected subset. Consequently, minute papers can provide the instructor with formative assessment of student learning that can be used to inform future instruction and isolate potential misconceptions held by students regarding course material.

Minute papers are most commonly used during the last few minutes of a class period as the instructor asks some variation of the questions: (1) What is the most important thing you learned today? (2) What is the muddiest point (most confusing concept) remaining at the conclusion of today's class? (Stead, 2005; Anderson and Burns, 2013). To close the loop on the use of this strategy, an instructor would ideally begin the next class by clarifying the most commonly cited muddiest points (Chizmar and Ostrosky, 1998) or address these items elsewhere in subsequent lectures

(Barnes, 2008). Alternatively, instructors may use the minute paper activity to have students submit potential exam questions (Murck, 1999).

#### *How It Is Active*

Minute papers are mainly opportunities for student reflection, and the outcomes of these reflections can be used to increase student–instructor communication within the classroom (typically during the next class meeting). They do not increase peer-to-peer interaction (unless specifically designed to do so) and typically do not provide students with additional experiences.

#### *Research Validation*

The evidence of effectiveness associated with minute papers is made up of both empirical research (Almer et al., 1998; Chizmar and Ostrosky, 1998; Das, 2010) and publication of practitioner wisdom (Harwood, 1996; Murck, 1999; Orr, 2005; Stead, 2005; Barnes, 2008). Despite the simplicity of the strategy, relatively little research has investigated the impact of this technique on student learning. Chizmar and Ostrosky (1998) describe applying the minute paper activity to both online and face-to-face classes in introductory economics and suggest that regular feedback from students to the instructor on their learning increases their engagement in the course. Student learning gains, as measured by pre- and posttests, were significantly higher in classes that incorporated the minute paper strategy (treatment) than in classes that did not use minute papers (control) and was not dependent upon instructor or student ability (Chizmar and Ostrosky, 1998). Almer et al. (1998) found that performance on essay-type quizzes was significantly better for accounting students who completed minute papers, but there was no difference for multiple-choice quizzes. Students who completed ungraded minute papers outscored students who were told that their minute papers would be graded (Almer et al., 1998), supporting the formative, rather than summative, application of this strategy. Das (2010) empirically applied the technique to a statistics course and found that generating minute papers significantly and positively affected students' learning in the course when compared to sections not using the practice.

#### *Preclass Preparation*

Minute papers require relatively little preclass instructor preparation beyond the identification of an appropriate writing prompt. The deployment of a minute paper activity is not reliant on specific technology or tools, but the instructor may have an easier time reviewing results by providing similar-sized pieces of paper for students to write on. Prompts may be prepared prior to instruction or may be generated on the fly during class in response to specific events or perceived deficits in student understanding.

#### *Student Strategy Use*

For the student, an anonymous minute paper activity is intuitive and can provide a low-stakes opportunity to freely respond and reflect on their knowledge of a concept or topic. Although the use of minute papers can lead to students' active involvement in their learning process via the asynchronous communication of their thoughts with the instructor, the activity itself does not inherently lead to an increase in peer interaction. The brevity of the minute paper exercise makes assessment relatively straightforward, because the instructor can sort through a representative selection of responses after class to confirm students' grasp of concepts or identify gaps in learning. Orr (2005) reported that students in his Introduction to Literature class were reticent to ask questions during class but would often include perceptive inquiries in his end-of-class minute papers activities that he would then use to prompt discussion at the start of the next class meeting (see also Stead, 2005). Harwood (1996) suggested that instructor praise of questions collected from the minute papers resulted in an increase in student questions during class. Instructors may share selected answers to minute papers at the next class meeting to illustrate the best representations of class concepts and model the format of effective minute paper responses.

#### *Task Characteristics*

Minute paper exercises can be administered at the beginning of class to activate prior knowledge or conceptions on a topic, midclass as a transition between tasks or topics, or at the end of class to wrap up a suite of activities or concepts. While the application of minute paper activities can take relatively little time, Stead (2005) noted that repeated use of this strategy during a single class could lead to student burnout if instructor prompts were not specific or if there was not enough material covered between prompting events. While applicable in all class sizes, larger classes present more challenges related to the collation and consideration of results, though this limitation can be substantially remedied through the random selection of a representative subset of responses. Murck (1999) integrated random, low-stakes minute paper activities into her large introductory course as a way of ensuring consistent attendance.

#### *Summary*

We categorize minute paper activities as a strategy with high utility and moderate learning efficacy. This is one of the most straightforward active learning strategies to implement, because it requires almost no resources and the instructor can potentially use the same two questions during every implementation. It is also one of the few activities that provides students an opportunity to explicitly identify the content that they thought was most important, as well as material that is proving challenging. Consequently, the instructor has an opportunity to directly intervene in subsequent classes to resolve ambiguity in student understanding. Such a process may give students a greater sense of ownership in the course and their own learning and increase student engagement.

### Peer Instruction (Conceptests)

#### *Description*

Peer instruction represents one of the most widely used teaching strategies in introductory courses across a range of STEM disciplines (e.g., Henderson et al., 2012; Vickrey et al., 2015). Peer instruction originated with Eric Mazur, who used the strategy in his introductory physics course (Mazur, 1997). In this technique, an instructor follows a lecture segment by posing a conceptual multiple-choice question (conceptest) that focuses on a single key concept. Students may answer the conceptest individually (Crouch and Mazur, 2001) by raising their hands (e.g., Landis et al., 2001), using lettered answer cards (e.g., Jones et al., 2001; Meltzer and Manivannan, 2002), completing answer sheets (e.g., Rao and DiCarlo, 2000) or using a classroom response system commonly referred to as clickers (Greer and Heaney, 2004; Smith et al., 2009). The instructor then evaluates the student responses. The optimal range of correct student responses is 35%–70% (Crouch and Mazur, 2001). If fewer than 35% of the original responses are correct, either students do not understand the topic well enough to discuss the concept or the question is unclear or too difficult. If more than 70% of the class answered correctly, the question may have been too easy and additional discussion will yield little improvement in student answers or will result in most of those who did not initially choose the correct answer selecting the most popular choice without understanding why (Crouch and Mazur, 2001). When correct responses are between 35% and 70%, students are instructed to discuss the reasoning behind their choices with their neighbors (peer instruction) in pairs or small groups and vote a second time (Mazur, 1997). The instructor then provides an explanation for the correct answer.

### How It Is Active

Peer instruction and conceptests facilitate high levels of peer-to-peer interaction, student–instructor interaction, and (via the consideration of personal and aggregate responses) student reflection of learning during the class period. They do not, however, provide significant opportunities for student experiences by doing or observing unless a conceptest is designed around a demonstration.

### Research Validation

Research reveals that peer instruction produces significant learning gains in a variety of class settings and disciplines (Crouch and Mazur, 2001; Smith et al., 2009, 2011; Vickrey et al., 2015), with specific examples from the geosciences (Greer and Heaney, 2004; McConnell et al., 2006; Mora, 2010). Most of these data compare pre- and posttest results before and after instructors incorporated peer instruction. The strategy has utility for both instructor and student: the instructor receives a rapid indication of how well students comprehend a key concept as it is being taught, and students have an opportunity to measure their learning against a standard defined by the instructor, as well as against their peers. One caution about the use of peer instruction is that while this technique is relatively well known, it is often misapplied (Henderson et al., 2012; Dancy et al., 2016). That is, instructors may forgo the peer-discussion aspect of the strategy and reduce the experience to a multiple-choice quiz. In simplifying the process, an instructor removes the opportunity for students to build on their knowledge through interaction with peers (Turpen and Finkelstein, 2009).

### Preclass Preparation

Effective conceptests take careful preparation to ensure that the question isn't so easy that the answer is obvious to almost all students or so difficult that peer instruction doesn't improve student performance. Instructors may generate their own conceptests or use existing conceptest collections, such as the more than 300 geoscience conceptests available from SERC (see Supplemental Materials). Most instructors already have a collection of multiple-choice questions, some of which would be suitable to use as conceptests. Alternatively, many questions in the Geoscience Concept Inventory would make appropriate conceptests (Libarkin and Anderson, 2005; Libarkin et al., 2011). The instructor can use this strategy without supplying additional resources to the students or can use appropriate clicker technologies, which are increasingly common on most campuses.

### Student Strategy Use

Both students and instructors are familiar with multiple-choice questions and how to use them. Consequently, peer instruction has the potential to be straightforward to incorporate into lessons. Peer interaction can be readily encouraged around a single question among formal or informal pairs or small groups of students seated near one another in class. While the instructor may use the proportions of raised hands or colored cards to obtain a qualitative sense of student learning, student response systems increasingly allow quantitative data to be collected and grades to be assigned to student participation or performance. Access to the hardware and software necessary to support these systems may constrain their use in some settings.

### Task Characteristics

Individual conceptests may take a few minutes to complete while posing the question, collecting an initial round of student responses, allowing time for peer interaction, and collecting and analyzing a second round of responses (if appropriate). Wait times between posing a question and collecting responses will vary from about 30 seconds to a few minutes, depending on the character of the question. If class time is at a premium, instructors may have students skip the individual responses and immediately confer with their peers to select the most appropriate response (Vickrey et al., 2015). However, students report that the extra time for individual reflection is valuable and skipping this step resulted in less peer discussion in an introductory physics course (Nielsen et al., 2016). The number of peer instruction opportunities would vary among classes depending on the topic and the incorporation of other teaching strategies. Following Mazur's (1997) original format and dividing the class into short lecture segments (10–15 minutes) followed by one or two conceptests would yield the need for approximately three to six conceptests per lesson for a 50-minute class. The strategy can be readily applied in classes of almost any size. Especially with the use of clickers, an instructor can gauge the proportion of correct responses as readily in a class of 200 as in a class of 20.

### Summary

We categorize peer instruction as a strategy with high utility and high learning efficacy. Peer instruction using conceptests is one of the instructional strategies with the clearest benefit for both instructor and student. This research-validated strategy is straightforward to use and assess, requires few resources, can be applied in almost any class setting, and is supported by an extensive collection of sample conceptests.

## Role Playing

### *Definition*

Role playing is a simulation activity that asks students to take on the roles of people who will affect, or be affected by, a topic or phenomena. Role playing can result in students confronting situations from the perspective of others and can promote both cognitive and emotional aspects of learning (Kilgour et al., 2015). This strategy encourages students to think and brainstorm about complex issues that often lie at the intersection between science and society. In its simplest form, an individual role playing activity may ask students to assume the role of a community member writing a letter to a local council person or state representative. Interactive role playing, in which students work together in small groups, may help develop teamwork and build analytical and communication skills (Bair, 2000). Role playing has been used in nursing (Chan, 2013), astronomy and physics (Francis and Byrne, 1999), multicultural and mathematics education (Kilgour et al., 2015), and geoscience classes teaching about land-use planning (Anastasio and Latta, 2000), climate change (Harwood et al., 2002), volcanic eruptions (Harpp and Sweeney, 2002), earthquakes and typhoons (Barrett et al., 2003), and dam failure (Hales and Cashman, 2008). For example, Harwood et al. (2002) used role play to simulate a Senate subcommittee hearing on global climate change in an integrated science course for preservice teachers. Students were assigned roles as senators (on the Congressional Committee on Energy and Natural Resources) or representatives of special interest groups (e.g., the Sierra Club, Environmental Protection Agency, and Centers for Disease Control and Prevention), drafted a position statement, and argued their case to the Senate members (Harwood et al., 2002).

### *How It Is Active*

Role playing augments peer-to-peer interactions and provides students both doing and observing experiences during the planning and enactment of the role scenarios. It does not necessarily provide students with opportunities for reflection, and the level of student–instructor communication may not be increased depending on the structure of the assignment (e.g., if the roles are played out in a set sequence without instructor input).

### *Research Validation*

Role playing has been applied in geoscience courses via a variety of mock hazard scenarios. Although plentiful role playing examples are available, publications most often are classified as practitioner wisdom or case studies explaining their implementation. Publications cite minimal evidence of role playing affecting student learning, though role playing has been shown to improve student confidence in science communication (McEwen et al., 2014) and is posited to improve student analytical skills (e.g., Bair, 2000).

### *Preclass Preparation*

Significant instructor preparation is required to formulate a role playing scenario and devise and assign roles. Role playing works best when instructors assign roles in advance so that students have time to research and prepare for their assigned role. Instructors will need to provide suitable resources to students either through handouts in class or through preclass reading and/or as research assignments. The role playing activity may require little more than a suitable classroom space. Links to examples of a variety of geoscience-themed role playing scenarios are provided in Supplemental Materials.

### *Student Strategy Use*

Student involvement and lively participation are crucial for role play. Any role playing scenario needs to be carefully designed so that students are well prepared and have sufficient direction so that they are familiar with their roles and responsibilities. Role playing can take multiple interactive forms in the classroom, such as a townhall-style debate, a model United Nations summit, or students working together to solve a complex problem. These styles of role play may involve high levels of student–student interaction. In most cases, small teams of students collaborate to prepare and carry out their roles in the activity, and students respond to arguments and ideas presented by other teams or students during the activity. Assessment of student degree and quality of participation in the activity presents several challenges. It may be more straightforward to assess student performance on a subsequent writing task or on related exam questions.

### *Task Characteristics*

Significant in-class time is required for the scenario to play out, ranging from one class period to multiple classes. Consequently, relatively sophisticated role playing may be used sparingly during the semester. Finally, instructors will find it challenging to assign equivalent roles to all students in moderate to large classes.

### *Summary*

We categorize role playing as a strategy with low utility and low learning efficacy. This strategy is best suited to smaller classes and instructors seeking a teaching experience that merges geoscience content with societal issues. Departments that seek to provide students with training in development of their communication skills may find that role playing scenarios represent a potentially interesting, team-based approach to instruction.

## Teaching With Models

### *Description*

Everyone routinely uses models—systems of objects or symbols—to communicate concepts and represent complex ideas and systems (Gilbert and Ireton, 2003). The use of models in the geosciences may take many forms (MacKay, 2017), but in the context of this paper, we will focus on student handling of physical models and an instructor manipulating models during lecture demonstrations. Models can both present students with an accessible method to understand basic scientific concepts and provide opportunities for students to compare and contrast the features of the model with its natural analog. Gray et al. (2010, 2011) discussed incorporating inexpensive, easy-to-construct physical models into large (~150 student) Earth Science classes. In larger classes, instructor-driven interactive lecture demonstrations may be more applicable than sharing models among groups of students (e.g., Sharma et al., 2010). These demonstrations typically involve three parts: (1) an initial opportunity for students to predict the outcome of the demonstration, (2) students watching the demonstration, and (3) students considering the outcome, comparing it with their initial prediction, and interpreting the result of the demonstration (Sokoloff and Thornton, 1997).

### How It Is Active

Teaching with models has the potential to provide significant and authentic observing experiences in a classroom. Depending on whether students have a role in the demonstration or manipulation of a model, this strategy may also provide doing experiences. Unless designed as a group activity, the use of models may do not automatically augment peer-to-peer interaction. Finally, reflection is not an inherent feature of this strategy.

### Research Validation

Models have been shown to improve student learning in a variety of STEM disciplines, such as anatomy (Yammine and Violato, 2015), biochemistry (Harris et al., 2009; Forbes-Lorman et al., 2016), chemistry (Hageman, 2010), physics (Crouch et al., 2004; Sharma et al., 2010; Brewe et al., 2013), and Earth Science (Gray et al., 2010, 2011). Furthermore, the use of models resulted in more positive student attitudes about the discipline (Gray et al., 2011; Brewe et al., 2013) and has contributed to closing the gap between genders in the understanding of key aspects of biochemical literacy (Forbes-Lorman, 2016). Interactive lecture demonstrations have been widely deployed in physics and have produced significant learning gains in comparison to traditional lecture (e.g., Sharma et al., 2010). Modeling procedures on their own may not result in a change in student understanding (Milner-Bolotin et al., 2007). For example, Crouch et al. (2004) reported that student learning gains were diminished if students did not have an opportunity to complete the prediction and discussion phases of the interactive lecture demonstration cycle.

### Preclass Preparation

Models may be readily adapted for use in small classes or lab sections (e.g., Frey et al., 2003; Swope and Giere, 2004) but present a challenge, and potential expense, in large classes if the instructor seeks to go beyond interactive lecture demonstrations (e.g., Harpp et al., 2005). The use of models and/or demonstrations in class requires some preparation; the amount of preclass effort will depend largely on the types of resources needed, format of the models, and size of the class. Interactive lecture demonstrations, whether presented directly in class or through an animation or video, may represent a more accessible alternative for large classes. There are more than a hundred demonstrations suitable for geosciences classes available on the SERC Pedagogy in Action site (see Supplemental Materials).

### Student Strategy Use

The most basic models should be relatively intuitive for students to use, but models of more complex systems may require the instructor to devote time to orient the students to the modeling task. Models may have multiple parts and thus require the interaction of multiple students to use the model and interpret its characteristics. While models may provide students with physical analogs for natural processes, any attempt to measure student learning typically requires that they complete an associated exercise or worksheet as part of a formative or summative assessment. Gray et al. (2010) described a class setting in which students were guided through relatively brief (5–10 minute) model tasks and were subsequently assessed on their comprehension of key concepts using conceptest style questions and a personal response system (clickers).

### Task Characteristics

Gray et al. (2010) reduced time needed for implementing each model by placing students in permanent small groups and having representatives from each group collect the model materials at the start of each class. The use of physical models or interactive lecture demonstrations typically require at least several minutes of class time, and the organization and space required to use these strategies may make it impractical to execute multiple examples per class. While some authors have used these strategies in large classes (e.g., Gray et al., 2010), the amount of resources required for some models and demonstrations may mean that some activities are limited to small or moderately sized classes.

### Summary

We consider teaching with models to have moderate utility and high learning efficacy. Teaching with models can support student learning through engaging, interactive activities but may require more preclass preparation and resources than some other active learning strategies.

## Think–Pair–Share

### Description

Think–pair–share is a strategy designed to get students talking to each other about course content in response to an instructor prompt. Students are provided with a problem or question and (1) individually reflect on their answer, (2) pair up with a classmate to discuss a potential response and (3) share their thoughts with the rest of the class and instructor. As with many of the strategies discussed in this work, think–pair–share is built on a constructivist paradigm for learning, which states that students construct their knowledge during social interactions about a phenomenon by placing it in the context of their own experiences (Vygotsky, 1978). The instructor may use this activity as a way to introduce students to a concept or as a formative assessment during a lesson or summative assessment at the conclusion of a lecture segment.

### How It Is Active

Think–pair–share activities inherently increase peer-to-peer interaction and student–instructor communication. They do not provide opportunities for reflection or provide students with distinct experiences beyond whatever may be included as a prompt for the specific activity.

### Research Validation

Think–pair–share activities are rarely discussed on their own (see Fitzgerald, 2013) and are more frequently studied as a component of a set of activities used in active learning environments (Macdonald and Korinek, 1995; Reynolds and Peacock, 1998; Yuretich et al., 2001; Greer and Heaney, 2004). Students have responded positively to think–pair–share exercises as part of a set of activities in an introductory oceanography course, stating that it "allows us to become more involved in discussions" (Yuretich et al., 2001, 117). Similarly, Fitzgerald (2013) found that the introduction of this technique in a large lecture class for nursing students increased proficiency scores and was positively received by the students. However, the adoption of this method was in tandem with a redesign of the course that required students to review audio recordings of lectures before attending class (Fitzgerald, 2013), and the think–pair–share strategy was modified to such a degree that it had as much in common with lecture tutorials as it did with the description of the strategy above.

### *Preclass Preparation*

Think–pair–share activities require little or no additional class resources beyond the identification of a prompt for students to engage in the activity. The instructor may pose a question or ask students to interpret a photograph, analyze data presented in a graph, or explore their preexisting ideas about a topic at the start of a lesson (see Supplemental Materials). This content may already be part of lecture presentations. This strategy shifts some responsibility for explaining the item's features from the instructor to the students. Instructors who routinely ask, "Are there any questions?" may find that the use of think–pair–share activities provides a mechanism to encourage more thoughtful and frequent student responses and resulting class discussion.

### *Student Strategy Use*

Student use of think–pair–share is relatively intuitive and requires little direction. The latter two steps in the strategy ensure student–student interaction and student–instructor interaction to construct an effective response to the original prompt. This strategy provides an opportunity for instructors to model effective approaches to analyzing geoscience questions, data, and/or images. Think–pair–share is typically used for formative assessment and is designed to end with a community-generated, instructor-guided response. This might include time for students to summarize responses (Macdonald and Korinek, 1995) as a record of the lesson. Instructors seeking to track student responses may use clickers or paper worksheets. Greer and Heaney (2004) used this technique to collect feedback electronically in an instructor-facilitated group format.

### *Task Characteristics*

Think–pair–share activities represent a relatively low investment of student time, typically a few minutes per task. There are relatively few class size constraints except when an instructor sought to collect and score student work products. Otherwise, if the principal result (share) is student participation in a whole-class discussion, the instructor can informally gauge the success of the activity on the basis of the depth of understanding evident from the resulting student dialog. Think–pair–share activities can be applied several times during a single class as a way to gauge student learning after each lecture segment.

### *Summary*

We consider the use of think–pair–share strategy to have high utility and low learning efficacy. This strategy has the potential to support student learning without the need for additional resources, instructor grading, or complex class organization and can be easily adapted to use with existing lecture resources. The principal limitation of the strategy is the relative paucity of research findings in support of the think–pair–share resulting in an improvement in student learning.

## DISCUSSION

We categorized strategies on the basis of their effectiveness at promoting student learning (Table I) and their utility (Table II). Strategies that have a high utility have a number of features that make them easy to use: for example, they are straightforward to prepare, examples are readily available, and they can be used frequently during a lesson in any size classroom. Strategies with moderate or low utility require more time investment for teacher preparation and assessment and would likely not be used as often or as readily in larger classes. The utility score is not intended as a value judgement of any particular strategy. It is not our intent to identify one strategy as better than another, because learning environments show so much variation that instructors should select the strategies that represent the best fit for their classes and interests.

### Composite Strategy Scores

Average utility scores were relatively evenly distributed among the three categories (preclass preparation, student strategy use, and task characteristics), with each of the nine component criteria averaging moderate to moderate-high scores, ranging from 1.91 (potential use frequency) to 2.55 (class size limitations). Combining utility and learning efficacy scores yields a total composite score for each strategy (Table III). The minimum possible score would be 10, and the maximum score that could be achieved using our scoring schemes would be 33. While all of these strategies are designed to provide the student and the instructor with an opportunity to assess student learning, the three highest-scoring strategies (peer instruction, think–pair–share, and minute papers) are characterized by questions or prompts that produce a relatively rapid student response with a modest investment of instructor preparation and instructional time. In contrast, the lowest-scoring strategies (role playing and gallery walks) represent active learning techniques that may involve considerable preparation, be more challenging to direct in class, and have little evidence to indicate that they support student learning (Table III).

### Thinking Skills and Competencies

While we discuss the strategies individually, instructors may employ two or more of these activities in the same class, and many instructors may seek to incorporate strategies representing different levels of cognitive complexity. Strategies with a high utility are often characterized by tasks that use lower-order thinking skills of knowledge, comprehension, or application (Bloom et al., 1956). If instructors wish to encourage students to use higher-order thinking skills, they may seek to incorporate strategies that are rated as moderate or low utility. We classified variations in each of the active learning strategies according to Bloom's taxonomy (Table IV). Bloom's taxonomy divides cognitive learning into six levels, from lower-level thinking skills such as memorization to higher-order thinking that involves the evaluation of information. The taxonomy has been used by instructors in geology courses to guide the development of questions that address a range of cognitive skills (Fuhrman, 1996; McConnell et al., 2003). Bloom's classifications were

**TABLE III: Strategy utility and learning efficacy scores combined to yield a total strategy score. Strategies with highest scores are straightforward to prepare, are relatively intuitive for students to use, and require only a few minutes to be applied in most class settings. All but four of the strategies discussed are interpreted as having moderate to high learning efficacy on the basis of research findings.**

| | *Pre-Class Preparation* | | | *In-Class Actions* | | | *Task Characteristics* | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Instructor prep time: | Required resources: | Availability of examples: | Ease of student use: | Student interaction: | Assessment ease: | Class time needed: | Class size limitations: | Potential use frequency: | Research validated: | **Total score** |
| **Peer Instruction** | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 6 | **33** |
| **Think-pair-share** | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | **29** |
| **Minute Papers** | 3 | 3 | 3 | 3 | 1 | 2 | 3 | 3 | 3 | 4 | **28** |
| **Lecture Tutorials** | 2 | 3 | 2 | 3 | 2 | 2 | 2 | 3 | 2 | 5 | **26** |
| **Concept Maps** | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 3 | 2 | 5 | **26** |
| **Concept Sketches** | 2 | 3 | 2 | 2 | 2 | 2 | 2 | 3 | 2 | 2 | **22** |
| **Case Studies/Problems** | 1 | 2 | 3 | 2 | 2 | 1 | 1 | 3 | 1 | 5 | **21** |
| **Jigsaw** | 2 | 2 | 2 | 2 | 3 | 2 | 2 | 2 | 1 | 3 | **21** |
| **Teaching with models** | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 5 | **21** |
| **Gallery Walks** | 2 | 2 | 2 | 2 | 3 | 2 | 1 | 2 | 1 | 1 | **18** |
| **Role Playing** | 1 | 2 | 1 | 1 | 3 | 1 | 1 | 1 | 1 | 1 | **13** |

determined with a typical application of the strategy in mind. Variations in strategy application may alter Bloom's classification, meaning it is possible for a strategy to involve higher- or lower-order thinking skills.

Depending on course goals, instructors may want to support nondomain-specific competencies, such as writing skills, communication, and quantitative literacy, or affective goals, such as motivation, engagement, or interest. Some strategies with moderate to low utility have been shown to promote these types of nondomain-specific learning goals. Alternatively, the strategies can be subdivided on the basis of those that focus on visual representations of information (concept maps, concept sketches, and teaching with models) and those that emphasize verbal or written expressions of ideas (case studies and problem activities, jigsaw activities, gallery walks, and role playing).

## Implications for Instructional Change Process

Research on faculty professional development has shown that the biggest obstacle to faculty reforming their instruction is time (Henderson and Dancy, 2007, 2009; Henderson et al., 2011). This includes time to learn about effective teaching strategies, as well as the time needed to revise lessons to incorporate these new strategies. Having a clear idea of the utility and learning efficacy of various active learning strategies can play a valuable role in aiding instructors who are interested in reforming their course. When starting the revision process of a geoscience course, instructors would do best to begin by incorporating some of the higher-utility strategies. These are the most straightforward to use, but most importantly, there are an abundance of geoscience-specific examples available (see Supplemental Materials). As instructors become more comfortable using these higher-utility strategies, they can begin to incorporate some moderate- to low-utility strategies that require more preparation and class time but may target higher-order thinking skills. While use of the high-utility strategies may be relatively intuitive for participating students, incorporation of the moderate- to low-utility strategies may require some combination of instructor modeling and scaffolding to train students in how to use the strategies effectively.

Teasdale et al. (2017) and Budd et al. (2013) described the results of the classroom observation projects that characterized geoscience teaching through the application of the Reformed Teaching Observation Protocol (RTOP; Sawada et al., 2002). The RTOP instrument can be used to gauge the degree of active learning occurring in classes (Sawada et al., 2002), and geoscience classes have been

**TABLE IV: Classification of strategies by Bloom's taxonomy. Dark gray boxes indicate Bloom's level of the most common application or applications of activity. Light gray boxes indicate Bloom's level of less common applications of the activity. White boxes indicate activity does not typically incorporate that level of Bloom's taxonomy.**

| | Knowledge | Comprehension | Application | Analysis | Synthesis | Evaluation |
|---|---|---|---|---|---|---|
| **Peer Instruction** | | dark gray | light gray | | | |
| **Think-pair-share** | light gray | dark gray | light gray | | | |
| **Minute Papers** | | dark gray | | | | |
| **Lecture Tutorials** | light gray | dark gray | dark gray | light gray | | |
| **Concept Maps** | | light gray | light gray | light gray | dark gray | |
| **Concept Sketches** | | light gray | light gray | light gray | dark gray | |
| **Teaching with models** | | dark gray | dark gray | dark gray | light gray | |
| **Jigsaw** | | | | dark gray | dark gray | |
| **Case Studies/Problems** | | | dark gray | dark gray | dark gray | dark gray |
| **Gallery Walks** | light gray | dark gray | light gray | | | |
| **Role Playing** | | | light gray | dark gray | dark gray | dark gray |

characterized as teacher centered, transitional, or student centered depending on the degree of active learning occurring (Budd et al., 2013; Teasdale et al., 2017). While student-centered classes incorporate periods of traditional lecture, they typically feature frequent student activities (e.g., think–pair–share and small-group discussions), opportunities for student–student interaction, and instructors who facilitate learning by posing questions and monitoring student progress (Budd et al., 2013; Teasdale et al., 2017). Teasdale et al. (2017) report that more than two-thirds of student-centered classes devote at least 25% of class time to student conversations. Transitional classes are similar to student-centered classrooms but with less frequent activities and shorter periods of student–student interaction (Teasdale et al., 2017). Budd et al. (2013) noted that transitional lessons are characterized by two to five relatively brief questions or activities per class. Teacher-centered classes depend heavily on traditional lecture and involve few opportunities for student interaction, with more than 90% observed as featuring no student talk (Teasdale et al., 2017). Both Budd et al. (2013) and Teasdale et al. (2017) note that there are multiple pathways to a student-centered classroom featuring extensive use of active learning strategies and that instructors should adopt a holistic approach that emphasizes strategies that are most appropriate for their learning environment. Matching the characteristics of transitional and student-centered classrooms with the strategies presented here suggests that transitional classes are more likely to emphasize high-utility strategies (e.g., peer instruction, think–pair–share, and minute papers) while instructors teaching student-centered lessons will deploy strategies at all utility levels.

While discussion of these strategies has primarily focused on what happens in the lecture setting of the classroom, teaching strategies must also be considered within the context of the whole course experience. Higher-utility strategies are more straightforward to incorporate within one's normal teaching without much adjustment to schedule or content. However, as moderate- to lower-utility strategies are incorporated that require more class time for student activity and interaction, compensations may have to be made in the amount of time for direct instruction or the amount of content covered. One technique for accomplishing this is to use an instructional model in which students are tasked with learning some of the lower-order objectives and basic concepts outside of class (e.g., Gross et al., 2015). Instructors may also want to consider other outside-of-class assessment opportunities, such as mastery quizzes and writing assignments that are easily facilitated with online course management software (see Russell et al., 2016).

### Future GER and Development

One inescapable conclusion from this review is that there has been relatively little research conducted on the impact of most of these strategies on learning in the geosciences. With the exception of limited research on the application of peer instruction, lecture tutorials, and teaching with models, most discussions of the use of active learning strategies in geoscience classes can be classified as practitioner wisdom (e.g., concept sketches, role playing, gallery walk, and jigsaw activities). Some strategies (e.g., concept maps, minute papers, case studies and problem activities, and think–pair–share) are mentioned as part of a suite of activities that were incorporated in class designs that improved student performance, but there is little to show that these strategies individually increase student learning. There is a need for carefully designed DBER projects in the geosciences that seek to unravel the relative benefits of many of these active learning strategies. Furthermore, in most cases, the geosciences lack both available resource collections for particular strategies and related instructor stories about the implementation these strategies in specific courses. Collections of resources for moderate-utility strategies (e.g., concept maps, concept sketches, models, and jigsaw activities) linked to common course content would facilitate the implementation of these strategies in introductory courses and support professional development programs.

## CONCLUSION

It is our hope that this paper will serve as a decision-making guide for geoscience instructors to aid in reforming their classrooms by selecting and implementing some of the active learning techniques described above. Readers can adhere to the following guidelines when applying the resources within this paper:

1. Readers who may be new to active learning may choose to begin with one or two of the highest-utility strategies (peer instruction, think–pair–share, and minute papers) and explore the examples found in the Supplemental Materials to consider ways to incorporate the strategies into their teaching.
2. Those with some experience using active learning strategies may review Table III to discover active learning strategies that have properties similar to those of strategies they are currently using and may therefore be straightforward to incorporate into their classes. Alternately, they may wish to explore strategies that target specific skills (e.g., higher-order thinking).
3. Finally, readers who are familiar with a variety of active learning strategies may find that they have opportunities to provide new resources to the geoscience community or to interpret data from their courses to support the use of a strategy with limited research backing.

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