Commentary: ANALOGICAL THINKING IN GEOSCIENCE EDUCATION

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ABSTRACT
Geoscience instructors and textbooks rely on analogy for teaching students a wide range of content, from the most basic concepts to highly complicated systems. The goal of this paper is to connect educational and cognitive science research on analogical thinking with issues of geoscience instruction. Analogies convey that the same basic relationships hold in two different examples. In cognitive science, *analogical comparison* is understood as the process by which a person processes an analogy. We use a cognitive framework for analogy to discuss what makes an effective analogy, the various forms of analogical comparison used in instruction, and the ways that analogical thinking can be supported. Challenges and limitations in using analogy are also discussed, along with suggestions about how these limitations can be addressed to better guide instruction. We end with recommendations about the use of analogy for instruction, and for future research on analogy as it relates to geoscience learning.

INTRODUCTION
Consider the Earth's history as the old measure of the English yard, the distance from the king's nose to the tip of his outstretched hand. One stroke of a nail file erases human history. (McPhee, 1981).

In a few lines, McPhee's analogy conveys not only the magnitude of deep time, but also the fragility of human life on Earth. An analogy can be a powerful device, useful both for communicating old ideas and gaining insight into new ideas. In the geosciences, analogies are extremely common, perhaps because so much of the field deals with processes and forces that cannot be directly perceived and thus can often be known only through comparison to something else (see also Sibley, 2009). For example, when the basic concept of geologic time is first introduced, students are often asked to draw an analogy to something they know well, such as a 24-hour day, a calendar year, a tall building, or, as in the McPhee (1981) quote, the human arm (for further discussion of analogies for geologic time see Truscott, Boyle, Burkill, Libarkin, and Lonsdale, 2006). Likewise, to explain the convection in the Earth's interior, an instructor could make an analogy to the swirling of cream in a cup of coffee, or to water boiling in a pot. Such analogies often serve as frameworks for a student's knowledge, and may be extended by students when they are asked to explain geoscience phenomena, such as the structure of the Earth's interior (Libarkin, Anderson, Dahl, Beilfuss, & Boone, 2006). One need only open an introductory geoscience textbook to appreciate the vast number of analogies that geoscience students are exposed to.

The widespread use of analogies in geoscience education raises some important instructional questions: How do analogies work? What makes a good analogy? How can an instructor ensure that analogies are correctly understood? How can students' learning from analogies be supported and enhanced? This paper seeks to address these questions. Our approach is to consider analogy from a cognitive science perspective, drawing on empirical studies of analogical processing. We first discuss a theoretical framework for analogy from the field of cognitive science, *structure-mapping* (e.g., Gentner, 1983; Gentner & Markman, 1997), that describes the processes of analogical comparison. We will focus on three main steps: (1) retrieving knowledge about the examples in the analogy, (2) comparing the two examples on the basis of the relationships that they have in common, and (3) making inferences about the examples based on their common relations. We use prior research on analogy from cognitive science and education to: identify general characteristics of effective analogies, discuss different forms of analogical comparison (see Fig. 1), and assess cognitive supports for analogical comparison.

A main goal of our paper is to introduce a means of communication—a "hand-shaking protocol"—between cognitive science researchers and geoscience instructors for discussing the use of analogy in geoscience practice and education. Geoscience instructors use analogy in a variety of ways, often (but not always) effectively. Cognitive scientists can introduce an understanding of why particular methods are effective or how they are related in terms of their demands on student cognition. Cognitive scientists also can learn from the rich use of analogy by geoscience instructors, who have developed an extensive inventory of instructional techniques to convey processes that unfold over vast spatial and temporal time scales.

WHAT IS ANALOGICAL THINKING?
Analogy is a kind of similarity in which the same system of relations holds in two different examples. For instance, when a person is told that the interior of the earth is like a peach, they are unlikely to assume that a

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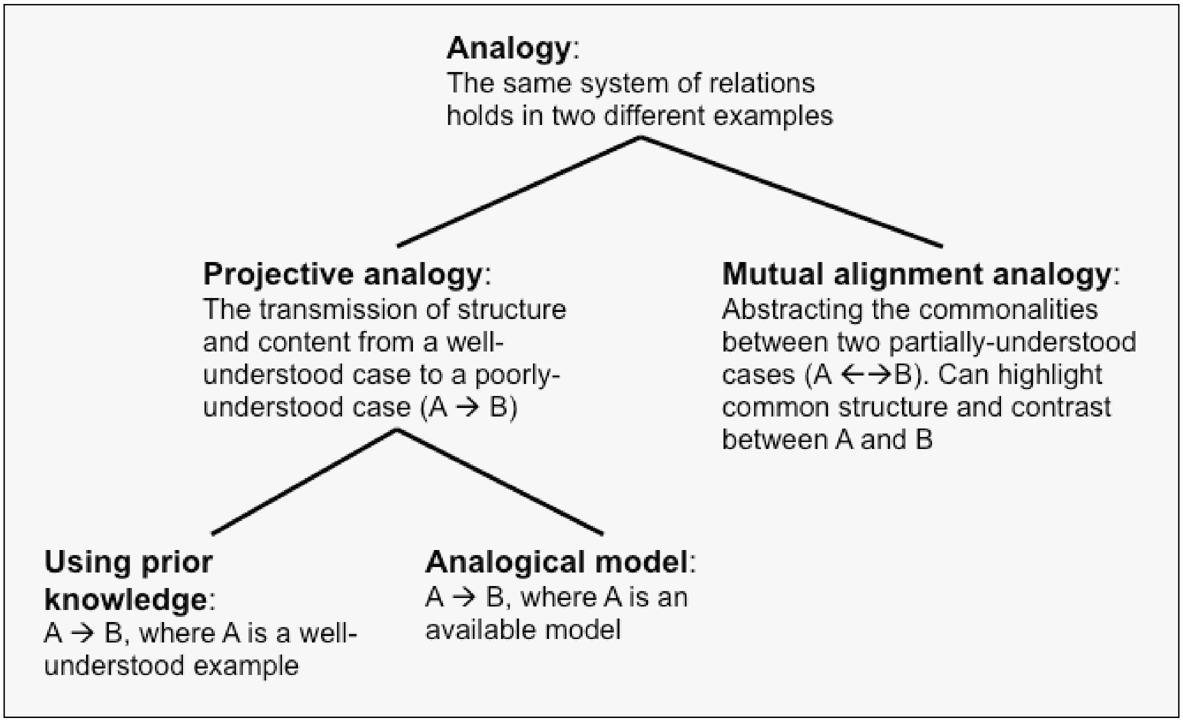

FIGURE 1. Different forms of analogical comparison.

substance with the taste, color, and texture of a peach can be found beneath the earth's crust. Rather, they understand the message to be that comparable spatial relationships hold within each of the two objects. The analogy states that their parts—the skin/crust and pit/core—relate to one another in the same way. Effective analogies thus capture *common systems of relations across different examples* (Gentner, 1983). Once the commonalties between two systems have been established, the student can ask whether further inferences from one example to another might also hold. In the case of the analogy between the interior of the earth and that of a peach, the student can make inferences about the relative thickness of the earth's crust and the solidity of the core based on their knowledge about the corresponding parts of the peach. The advantage of utilizing analogy, from an instructor's point of view, is that analogy is very often the best way to convey an entire system of relations in a new, unfamiliar example.

The key step in understanding an analogy is arriving at a structural alignment—a set of correspondences that reveals the common relational system embodied in both analogs. Research has shown that analogical comparison typically renders the common relational pattern more salient to the student (Gentner & Namy, 1999; Markman & Gentner, 1993) and more likely to be transferred to future cases (Gentner, Loewenstein & Thompson, 2003; Gick & Holyoak, 1983). Thus analogies can help students gain an explicit understanding of the principles in a domain. Further, once the common relational system is discovered, students can use their knowledge of the source to make further inferences about the lesser known domain (as amplified later). Thus the process of structural alignment has two potential advantages: it helps students to abstract the relational principles common to both analogs, and it invites inferences that increase understanding of a concept that was previously unfamiliar.

The term *analogical mapping* refers to the process of finding commonalities and drawing inferences between two examples. An interesting—and useful—fact about analogical processing is that adults (though not necessarily children) generally prefer analogical mappings based on relational commonalities, such as common causal or spatial structure, rather than concrete commonalities (such as matching color, shape, or size). This implicit preference contributes to analogy's usefulness in discovering common relational principles, as discussed earlier. This preference for finding correspondences on the basis of common relational structure, predicted by structure-mapping theory (Gentner, 1983), has been confirmed in a wide range of studies (Gentner & Clement, 1988; Goldstone & Medin, 1994; Holyoak & Koh, 1987; Jones & Love, 2007; Keane, 1996; Krawczyk, Holyoak, & Hummel, 2004; Markman & Gentner, 1993).

An important contribution of structure-mapping theory is that it analyses analogical comparison into several steps. To illustrate these steps, consider how a student attempts to understand the following analogy about mountain elevation (based on material from an introductory earth science text by Marshak, 2005, pp. 77-78):

> The extra thickness of continental crust beneath mountain ranges is the reason for their high elevations. The crust holds the lithospheric mantle up; the thicker the crust, the higher the lithosphere floats. It is like when a buoy supports an object in the water.

In this example, the buoy in the water, with an object attached, is the *source* for the analogy; the case that we

TABLE 1. FACTS INVOLVED IN THE FLOATING BUOY/MOUNTAIN ELEVATION ANALOGY

FACTS ABOUT SOURCE: FLOATING BUOY		FACTS ABOUT TARGET: MOUNTAIN RANGE
Object attached to buoy	→	Lithospheric mantle
Buoy	→	Crust
Water	→	Asthenosphere
S1: A buoy is made of material that is less dense than water.		T1: The continental crust is less dense than the asthenosphere.
S2: An object attached to a buoy will float.		T2: Continental crust lifts up the lithospheric mantle below it.
S3: The height to which an object attached to a buoy will float depends on the overall density of the object plus the buoy.		T3: The height to which the lithosphere will elevate depends on the overall density of the lithospheric mantle plus the continental crust.
S4: An object attached to a larger buoy will float higher.		T4: Lithosphere with thicker continental crust will elevate higher.
S5: S1 explains why S2 is true.		T5: T1 explains why T2 is true.
S6: S3 explains why S4 is true.		T6: T3 explains why T4 is true.

assume is familiar to the student. The elevation of a mountain range is the *target* of the analogy; this is the case that is less understood and that the instructor wants his or her students to learn about. To begin to comprehend the analogy, the student must retrieve knowledge about the source example from memory. If the analogy is well-chosen, there will be a good deal of relevant knowledge stored with the source example. This knowledge, represented in schematic form as a set of statements, could include the facts listed on the left side of Table 1.

Having retrieved knowledge of the source from memory, the student must *align* the two analogs—that is, determine which elements of the source correspond to which elements of the target. As discussed above, the student will seek correspondences based on common relational structure between the source and target. Because the relationship between the continental crust and the lithospheric mantle is like that between a buoy and an object attached to it, the buoy must correspond to the crust, and the attached object to the lithospheric mantle. If students possess some knowledge of the Earth's interior, they can also determine that the water in the buoy example corresponds to the asthenosphere.

With these correspondences in place, the source and target are connected by a structure-mapping. Students can then use their knowledge of the source example to draw inferences that can flesh out their understanding of the target. The inference step involves a kind of selective pattern completion: knowledge that is connected to the common system in the source, but not yet present in the target, is projected to the target as a *candidate inference* (Falkenhainer, Forbus, & Gentner, 1989). The inference step represents an especially powerful aspect of analogical instruction. Through an established structure-mapping, the student can import further information from the source to the target. In the case of geoscience analogies, this mapping may include important spatial, temporal, and causal relations in addition to attributes of objects.

To summarize, analogical comparison involves several steps: retrieving knowledge of the source from memory, establishing correspondences between the source and target on the basis of common relational structure, and making inferences based on an established structure-mapping. If all goes well, the end result is a better understanding of the target domain.

The first step in supporting students' analogical thinking is to provide effective analogies. However, the effective use of analogy for geoscience education depends on more than finding a suitable example with which to compare some novel concept. Even with potentially useful analogies, students can have difficulty recalling the relevant source information, performing alignment and structure-mapping, or drawing the desired inferences. Learning from any given analogy can be greatly influenced by the instructional efforts that surround it (e.g., Harrison & Treagust, 1993; Iding, 1997; Treagust, 1993). It is therefore important to consider how instructors can support students' analogical thinking.

SUPPORTING STUDENTS' ANALOGICAL THINKING

I. What makes a good analogy?

Our purpose in this paper is to provide general principles that can facilitate the design and implementation of analogies across a wide variety of geoscience topics. The general qualities of effective analogies are described by drawing on research involving analogical learning, using geoscience examples wherever possible. We also consider characteristics of *ineffective* analogies. While good instructors are careful to avoid poor analogies, contrasting effective and ineffective analogies will help to highlight the properties that make certain analogies better than others.

Inevitably, instructors will encounter two opposing goals in choosing analogies to present to their students. To the extent that the source analog is similar to the target, the student is likely to succeed in aligning the two examples. However, the resulting common system will still preserve many of the concrete particulars of the two exemplars. In contrast, if the source analog is very different from the target in its concrete particulars, the pair may be harder to align—but, if the student succeeds in aligning the pair, the resulting common system will be highly abstract and highly likely to carry across to other examples (e.g., Halpern, Hansen, & Riefer, 1990). A good analogy will involve an appropriate level of concrete similarity, such that students will be able both to align the source and target and to appreciate their abstract relational commonalities. The use of concrete similarity to support alignment and abstraction is discussed further below. First we consider good analogies in terms of retrieval of knowledge and structural consistency between the source and target.

i. Retrieving knowledge about the source. Students begin interpreting analogies by remembering what they know about the source example. The most basic element of a good analogy is that the source is familiar to the student (Harrison & Treagust, 1993; Joshua & Dupin, 1987; Taber, 2001; Thagard, 1992). This familiarity is far from trivial. Instructors' intuitions about what students already know can often be wrong. When students are unfamiliar with or misinformed about the source example, this misunderstanding can carry over to the target through analogical inference (e.g., Gentner, 1989; Johnson-Laird, 1983; Taber, 2001). For example, the well-known analogy from water flow to simple electric circuits often is used to help students understand electrical circuits (Gentner & Gentner, 1983). Students using this model to understand simple DC circuits could use the analogy to correctly predict that batteries in serial would lead to greater voltage than batteries in parallel, by analogy with water tanks: two tanks in serial—effectively one tall tank—will create greater pressure than two tanks in parallel, since pressure depends on the height of the water column. Yet, several students had faulty mental models of water flow; they thought water pressure depended solely on amount of water, not on the height of the column. This incorrect mental model led them to erroneously infer that serial and parallel batteries would lead to the same voltage (Gentner & Gentner, 1983). This example highlights the importance of ensuring that students have a correct model of the source domain to be used in an analogy.

The availability of a familiar, well-understood source case with the right structure increases the likelihood that students will correctly understand the analogy. For instance, most students are familiar enough with calendars to make a calendar year useful in an analogy for geologic time. General life experiences can be good sources as well. Hermann and Lewis (2004) suggested that the phases of human life could be a helpful example to use in an analogy for the structure of the geological timescale. Because the phases are partitioned into unequal units, such as childhood, young adulthood, and adulthood, with embedded subunits such as pre-teen and teen, the relational structure of a human timeline can align well with the hierarchical structure of the geologic time scale.

Another example of a familiar source for an analogy involves the explanation of how rocks obtain a paleomagnetic signal. Instructors often use an analogy with a compass needle, indicating that some minerals (notably, magnetite) act as small compass needles that get locked into position as the rock cools. This analogy has the advantage that any student unfamiliar with compasses can be given hands-on experience in the lab, a point developed further below.

ii. Alignment and structural consistency. With knowledge of the source example retrieved from memory, the student compares the two and arrives at a structural alignment between the source and target. Good analogies will involve a source and target that share significant relational structure. Consider a pair of analogies for the Great Missoula Floods that occurred during the last Ice-Age:

> *Analogy 1:* The glacier was like a glass of water holding Glacial Lake Missoula. When the glass tipped, the lake spilled out over the land.
>
> *Analogy 2 (based on Marshak, 2005):* The glacier was like a dam holding back Glacial Lake Missoula. When the dam abruptly burst, the lake spilled out over the land.

Analogy 1 correctly conveys that the glacier's movement caused the flood, but unfortunately also conveys an incorrect account of the process. Analogy 2 is a better match with respect to the causal event that precipitated the flood (since the glacier did not, of course, actually tip out the water, but simply ceased to block it).

iii. The use of concrete similarity. Instructors often use a source analog that differs greatly in concrete characteristics from the target. This has the advantage that the common abstraction stands out in sharp relief. However, students sometimes find it difficult to determine the relevant structural commonalities between the source and target. The task is especially difficult when the relational structure of the target is highly unfamiliar (Chi, Feltovich, & Glaser, 1981; Clement, 1998; Gentner et al., 2007; Jee & Wiley, 2007). In such cases, a close example can help pave the way to a more distant analogy (Clement, 1993; Kotovsky & Gentner, 1996). Concrete similarities between the objects, parts, and attributes of the source and target that support the desired relational match can help the student align the two examples (Gentner et al., 2007; Gentner & Toupin, 1986). For example, the roundness of the peach makes it easier to align with the structure of the earth. Another example with food as the source domain, described by Wagner (1987), is the use of layer cakes with different colored icing to teach about stratigraphy. Likewise, Francek and Winstanley (2004) report a lesson that involves students peeling an orange to gain a sense of the amount of useable soil on Earth (see Francek & Winstanley, 2004, for a detailed summary of the use of food in geoscience instruction).

When teaching about a topic that is highly unfamiliar to students, instructors should choose analogies that are high in both structural and concrete similarity. Indeed,

TABLE 2. EXAMPLE TARGET PROBLEMS WHERE OBJECT SIMILARITY IS CONSISTENT WITH STRUCTURAL OVERLAP VS. INCONSISTENT (CROSS-MAPPING)

	SOURCE	TARGET WITH HIGH STRUCTURAL AND CONCRETE SIMILARITY	CROSS-MAPPED TARGET
Problem statement	How many microscopes per chemist?	How many calculators per student?	How many students per calculators?
Problem form	# of microscopes / # of chemists	# of calculators / # of students	# of students / # of calculators
Mapping to source	N/A	Micro-scopes → calculators chemists → students	Micro-scopes → students chemists → calculators

research on analogical problem solving (that is, when students apply a known problem solution to a novel target problem) has shown that when corresponding objects in a familiar and novel problem are similar, people are more accurate in applying the solution from the familiar source to the novel target (Gentner & Toupin, 1986; Ross, 1987, 1989). For example, recalling the solution to a previously solved algebra problem of the form 'How many microscopes per chemist' can facilitate solution of a target problem that asks 'How many calculators per student'. Table 2 displays the structure-mapping for this pair of problems.

There is one case in which concrete similarities can make the mapping more difficult—namely, when the concrete similarities compete with desired relational match. This is the case in *cross-mapped* analogies (Gentner & Toupin, 1986, Ross, 1987, 1989). For example, a student who is asked to solve a target problem of the form 'How many students per calculator' could be impaired by using a source problem in the form 'How many microscopes per chemist', because the object matches run counter to the underlying structure of the problem. Table 2 shows that the structure-mapping for this source-target pair is inconsistent with the object-level matches. In general, cross-mapped analogies should be avoided in the early stages of learning, as they can lure students toward faulty mappings (Ross, 1989).

The preceding section covered some of the general properties of good analogies. We now turn to an important distinction between two different forms of analogy—*projective analogy* and *mutual alignment analogy* (Gentner & Colhoun, in press). Although these overlap in their processing, they have different characteristics and very different uses in instruction. We begin with projective analogies and then turn to mutual alignment analogies.

II. Projective analogies and analogical inference

Analogies are often used with the intention that the student will map knowledge from the source to the target (Gentner, 1983; Holyoak & Thagard, 1989; Markman, 1997). In many cases this is the instructor's main objective in presenting a given analogy: that is, the goal is to use an existing familiar source example to provide insight about a less familiar or more challenging target example. This kind of analogy, which Gentner (2005) calls *projective analogy,* is commonly used in instruction to teach about a new topic (e.g., Iding, 1997; Orgill & Bodner, 2006).

To understand a projective analogy, as noted earlier, the student must first align the source and target. Once this is done, then other information present in the source, and connected to the common system, may be considered as a possible inference. One characteristic of a good analogy is that it will support accurate and informative inferences. However, most analogies—especially between very distant domains—can potentially generate inferences that are irrelevant or downright wrong. For example, analogies that compare continental crust to a buoy in water can suggest to students that the asthenosphere is molten. Evaluating an analogy and its inferences involves several kinds of judgment (Gentner & Clement, 1988). One criterion is whether the analogy is sound: whether the alignment is structurally consistent, and whether the projected inferences follow from the analogy. A second criterion is the factual status (the accuracy, or at least the plausibility) of the projected inferences in the target. Candidate inferences are only hypotheses; their factual truth is not guaranteed by their structural consistency and must be checked separately. A related criterion, discussed by Keane (1996), is the adaptability of the inferences to the target problem. This type of evaluation may involve other reasoning processes such as causal reasoning from existing knowledge in the target. A third criterion is goal-relevance—whether the analogical inferences are relevant to the current goals (Holyoak & Thagard, 1989). An analogy may be structurally sound and yield true inferences, but it will still be of little interest if it does not address the question at hand.

To sum up, a good analogy will support inferences that are structurally sound, factually accurate (or at least plausible), and goal-relevant. To illustrate these constraints in action, consider the following widely-used analogy, illustrated in Table 3:

TABLE 3. FACTS INVOLVED IN THE BOILING WATER/MANTLE CONVECTION ANALOGY

FACTS ABOUT SOURCE: BOILING WATER		FACTS ABOUT TARGET: MANTLE CONVECTION
Water at bottom of pot	→	Lower mantle
Water at top of pot	→	Upper mantle
Heat source	→	Earth's core
S1: The stove heats the water at the bottom of the pot.		T1: The Earth's core heats the lower mantle.
S2: Heating lowers the density of water.		T2: Heating decreases the density of the mantle.
S3: Lower density water will rise.		T3: Lower density mantle will rise.
S4: Therefore, the water at the bottom of the pot will rise.		T4: Therefore, the material in the lower part of the mantle will rise.
S5: S1-S3 explains S4.		T5: T1-T3 explains T4.

> The convection of the mantle is like that in a simmering pot of water, where the Earth's core provides the heat.

From this alignment the student could make several potential predictions. Assuming that the student's goal is to understand the general process of mantle convection, the most goal-relevant, consistent, and factually viable inference would be that the heat produced by the Earth's core *causes* the lower mantle to rise.

The boiling water/mantle convection analogy is effective because the source and target share substantial relational structure, and many facts about the convection process can be projected from the simmering pot example. Yet, even though analogical inference is generally driven to find goal-relevant and systematic inferences, not all of a student's inferences will be accurate. For example, being a liquid is a highly salient feature of water. Based on the correspondence between the water and the mantle, it is inviting to infer that the mantle is a liquid. This is one place where the boiling water/mantle convection analogy breaks down, as the mantle remains solid during convection. For any analogy, there are some potential mistaken inferences, especially when very little is known about the target.

i. Physical models. So far we have discussed projective analogies in which an existing familiar source example is used to provide insight into a less well-understood target example. Such analogies are commonly used in teaching about a new topic. However, in some cases it is more convenient to construct a physical model as the source domain for teaching about a new topic. Sometimes this is because no appropriate source case is available, but there are at least two other reasons to use a physical model. First, it allows the instructor (and students) to vary the parameters and explore more aspects of the domain. Second, observing a concrete model can confer a kind of ground-level embodied understanding that can support future reasoning.

Learning from a physical model also involves projective analogy - in this case projecting observations and facts about an available source model to an unfamiliar target object or system. Like other projective analogies, models can have low surface similarity with their targets; for example, an instructor could model the ductile deformation of rocks by bending a sheet of paper. What is critical is that the elements of the model are related in the same way as in the object or system it represents. This relational similarity enables students to use their understanding of the model to make relevant inferences about the real-world system (see Sibley, 2009, for further discussion of how geoscience models can be analyzed as analogies).

Physical models have been used extensively for geoscience education, from the creation of artificial outcrops on a university campus (Benison, 2005; Kastens, Agrawal, & Liben, 2008) to the use of a lava lamp to model oceanographic principles (Tolley & Richmond, 2003). Play -doh and modeling clay are often used to represent geological layers, which can be used to characterize sedimentological principles (e.g., Law of Superposition) or deformed to show a variety of deformational geometries (e.g., folds and faults).

Models provide several valuable features for analogical learning. First, models can be idealized representations of the system, allowing them to clarify the important features of the target system. For example, "sandbox" models, comprised of horizontally compressed layers of sand, provide idealized models of faulting and folding and are used to study the deformation history of mountain ranges (Kastens & Rivet, 2008). Second, a model enables instructors and students to manipulate an object or system in ways that are impossible or impractical in nature. For example, models of groundwater systems allow students to manipulate the relationships between water table and pumping and observe the recovery of the system more easily than can be done in the field. Third, models can often remain available as students attempt to understand the analogy. The presence of the model decreases the burden on the student's mental resources, allowing the student to work through the structure-mapping and focus on comprehending the topic (e.g., Chandler & Sweller, 1991; Sweller, 1988).

What makes for a good model? The first criterion, of course, is that the model should clearly depict the desired aspects of the target topic. Second, good models will involve a source domain that is familiar, so that students can readily access knowledge about its states and processes. An example is using ketchup and other familiar substances to model the viscosity of silicate melts (Baker, Dalpé, & Poirier, 2004). Third, as with any analogy, alignment is easier if the source and target share some concrete similarities.

On the downside, physical models can lead students to rely too strongly on non-matching concrete aspects of the source. This can lead students to develop misconceptions about the real-world object or system that is represented. For example, if a model of volcanic eruption is inaccurate with respect to the scale of the volcano, the viscosity of the magma, and the time course of the eruption, students could acquire inaccurate beliefs about these properties. Thus, instructors should ensure that students attend to differences between the model and the target, as well as similarities (a point further amplified later).

III. Mutual alignment analogy

Thus far, we have discussed projective analogies, in which a well-understood source is used to understand a less-known target topic. But there is another important kind of analogy, in which the source and the target are both only partially understood. In these analogies, which Gentner (2005) referred to as *mutual alignment* analogies, the two analogs are typically both from the same domain or topic (e.g., both may be *synclines*) and are similar enough to be easily alignable. Mutual alignment analogies can be quite powerful because they can help students understand *both* examples better. For example, students are more likely to abstract the bowl-like geological structure that characterizes synclines by viewing two or more examples than they are if they see only one example. Likewise, students may be more likely to learn the general features that characterize a type of mineral, like graphite or pyrite, if they are shown multiple examples of these substances.

At first glance, comparing two similar examples from the same domain may seem very different from forming a mapping between a familiar topic and an unfamiliar topic. However, these two forms of comparison involve the same basic structure-mapping process, and both begin with structural alignment (e.g., Gentner & Markman, 1997; Markman & Gentner, 1993). That is, the process of comparing two partially-understood examples involves finding correspondences based on common relational structure, just as in projective analogy (Gentner & Markman, 1997; Kurtz, Miao, & Gentner, 2001). The difference is that in projective analogy, the goal is not only to notice common structure, but to import further structure from the familiar to the new topic. In contrast, in mutual alignment analogies, the chief goal is precisely for the student to notice and abstract the common system (Gentner et al., 2003; Kurtz et al., 2001; Markman & Gentner, 1993). An important benefit of mutual alignment is that it renders the common system more salient to the student. For example, people are far more likely to transfer a principle to a future example after comparing two examples illustrating the principle than after reading a single example (Gick & Holyoak, 1983) or even after reading the same two examples without comparing them (Gentner et al., 2003).

A further use of mutual alignment is to teach students about the variability within a given category. Examples of the same category can differ in many ways—in color, scale, orientation, and other features—and comparing across many instances of the same type can not only help students identify the criterial aspects of the category, but also the range of permitted variation. Experiencing more variable examples can also lead to a more general understanding of a concept, which may transfer better to new instances (e.g., Posner & Keele, 1968).

Another use of mutual alignment is for *contrast.* Once the two examples are aligned, differences connected to the common system stand out (Gentner & Markman, 1994; Markman & Gentner, 1993, 1996). For example, Jee, Uttal,

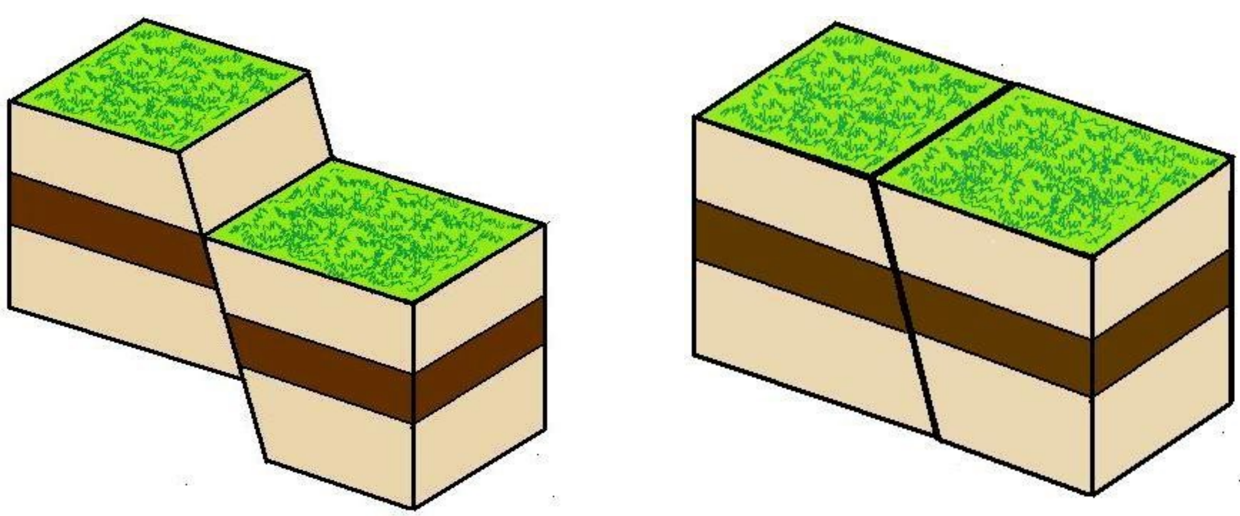

FIGURE 2. Highly similar contrasting images depicting a fault (left) and a fracture without a fault (right).

and Gentner (2008) found that beginning students can more easily grasp the concept of a *fault* - and how it differs from a fracture - if they compare an aligned pair of examples that are alike in every way except that in one case there is a simple fracture and in the other a fault (that is, slippage along the fracture) (see Figure 2).

A further use of contrast is to distinguish related but distinct categories. By comparing examples from different categories, a student can learn the properties that distinguish members of the two categories. Consider a student learning to distinguish between a *normal fault* and a *reverse fault*. Both involve a fracture in rock along which movement has occurred. The difference is that in a normal fault, the block of rock above the fault plane has moved down the slope of the fault, while in a reverse fault, the block moves up the slope of the fault (Figure 3). When examples are concretely similar, not only are they easier to align, but, once aligned, their key differences become more salient (Gentner et al., 2007; Gentner & Markman, 1994; Markman & Gentner, 1993). In fact, when two examples are identical except for a single difference, that particular difference is noticed relatively quickly and consistently (Gentner & Sagi, 2006).

To illustrate the advantage of mutual alignment in supporting contrast, consider again the images in Figure 3. Which pair of images, 1 and 2 or 2 and 3, would be most effective in teaching a beginning student the distinction between normal and reverse faults? Although each pair displays an example of each category, images 2 and 3 would be expected to be superior. In this case, the two images have more attributes in common, including the slope direction of the fault, its location, the degree of displacement along the slope, and the number of layers in the image. All of these concrete similarities should make it easier to determine which blocks of rock correspond to one another, and thus to determine that the rocks differ in terms of their relative movement across the fault.

IV. Instructional supports for analogical thinking

Besides using good analogies and avoiding ineffective ones, instructors can greatly influence how much students learn through the process of analogical comparison (e.g., Harrison & Treagust, 1993; Iding, 1997; Treagust, 1993). There are several ways that instructors can support students' analogical thinking and learning.

i. Ensure that students map the structure of the analogy. One way to help students' analogical comparisons is to have them explicitly relate the elements in the source and target. In other words, have the students explicitly complete the structure-mapping. Mapping the structure of an analogy motivates the student to think relationally, supporting their learning of the deeper commonalities between them. For example, Kurtz et al. (2001) showed people drawings of two scenarios, each depicting a different heat-flow situation, and gave participants different initial experiences designed to vary the intensity of their comparison process. Then the participants were given both scenes and asked to describe differences between them. The results were clear: the more intensive the initial comparison experience, the more likely people were to focus on differences relevant to heat flow, as opposed to shallow or idiosyncratic aspects of the scenes. Participants in the most intensive condition, who had written out correspondences and described commonalities, said things like "Heat is being transferred directly in **A** and indirectly in **B**." In contrast, people who had initially described the two situations separately said things like "You can eat the pancakes and drink the coffee."

These results have direct implications for instruction. For example, when using the floating buoy/mountain elevation analogy (Table 1), teachers could enhance students' learning by asking the students to spell out what the correspondences are: what object in the mountain elevation system corresponds to the buoy, to the weight attached to the buoy, and to the water, etc?. Such questions can help to highlight the relevant elements of the source, and prompt the student to find relational correspondences.

Students can also benefit when instructors state the correspondences explicitly. In a cross-national study, Richland, Zur, and Holyoak (2007) compared the use of analogies in classrooms in Hong Kong, Japan, and the U.S. The teachers in Asia explicitly stated the correspondences for analogies provided to students in math classes much more frequently than their American counterparts did. Similarly, learning from a model can be enhanced when instructors guide students while interacting with a model—for example, by making observations over time (Tolley & Richmond, 2003), predicting its behavior (Crouch, Fagen, Callan, & Mazur, 2004), or altering the model and observing the result (Gates, 2001). The Harrison and Coll (2008) guide to teaching with analogies

1. Normal fault **2. Reverse fault** **3. Normal fault**

FIGURE 3. Examples that may be used to teach the distinction between normal faults reverse faults.

provides a useful template for designing science analogies accompanied by several examples that can be used in middle and secondary school (although only a few geoscience analogies). In each case, the correspondences and inferences are explicitly given, as well as the disanalogous parts.

ii. Confronting erroneous inferences. No analogy is perfect, and analogies can sometimes lead to incorrect inferences. It is important that students confront the wrong inferences that an analogy can potentially generate, so as to be clear on the limits of the mapping (Kastens & Rivet, 2008). One way to do this is to spell out—or encourage students to generate—the incorrect inferences and to label them as such (see Harrison & Coll (2008) for examples). This can help prevent students from extending an analogy beyond its breaking point, and making incorrect inferences. Experienced instructors will have knowledge of the mistaken inferences that students are likely to make: for example, the inference that the mantle is a liquid in either the floating buoy/mountain elevation (Table 1) or the boiling water/mantle convection analogy (Table 2). If students understand where the analogy breaks down, they will be less likely to make subsequent errors. Kastens and Rivet (2008) suggest that students working with a physical model should be asked to generate both the similarities and differences between the model and the natural system. This can help students understand the relevancy of the model, but also its limits.

iii. Keep the source example present. Richland et al. (2007) argued that although U.S. teachers often provide good analogies, they often provide less of the support that would help students reap the most benefit from their analogies. They note that Hong Kong and Japanese teachers used techniques that reduced the cognitive burden on their students, such as providing visualizations of the source that remained visible as students processed the analogy. Keeping the source present aids the student in constructing a clear mapping between the source and target, and allows the student to direct their limited memory and attention resources toward *understanding* the commonalities between the examples (e.g., Sweller, 1988).

iv. Manipulating surface similarity. As noted earlier, it is generally easier to match two situations when the source and target are high in concrete similarity (Gentner & Kurtz, 2006). More important for our purposes, it is often the case that once students succeed with close (easily-aligned) pairs, they are better able to align and abstract from less similar pairs (Clement, 1993; Gentner et al., 2007; Kotovsky & Gentner, 1996). The initial concrete match enables the student to align the examples, making the common system more apparent and easier to discern in less concretely similar cases. This use of initial overall-similar comparison to bootstrap later more abstract comparisons has been called *progressive alignment* (Kotovsky & Gentner, 1996).

An example of scaffolding via close comparison can be seen in Marshak's (2005) introductory geoscience textbook. Throughout the book Marshak provides photographs of geologic structures accompanied by sketches of "what a geologist sees"—schematized colored sketches of the geological structure. By comparing the sketch and photo, the student can establish a structure-mapping between them, thereby clarifying their interpretation of the landscape. Similarly, in the geology textbook by Reynolds et al. (2007, p. xxv in the preface materials) students are asked to create their own sketches of illustrations. This practice is demonstrated in the opening section of the book. Such techniques involving visual analogies can be powerful teaching tools, but are often underused in science textbooks. Orgill and Bodner (2006) conducted an in-depth analysis of the analogies that appear in biochemistry textbooks, examining such characteristics as the location of analogies in the textbooks, the level of enrichment that the analogy receives, as well as the format of the analogy. Only about 15% of the analogies that Orgill and Bodner found were presented in visual format. Ideally, geoscience textbooks will contain high proportion of visual analogies, accompanied by the appropriate cognitive supports.

An instructional technique related to progressive alignment is the use of *bridging analogy*. In a bridging analogy, two disparate (but analogical) cases are linked by inserting a case that is intermediate between the other two examples (Clement, 1993). As in progressive alignment, the bridging case not only facilitates learning an abstract principle that binds the examples together, but enables the student to understand how the principle applies to each case. For example, students often have difficulty interpreting topographic maps (Rapp, Culpepper, Kirkby, & Morin, 2007), in part because the symbols and lines in the map do not resemble the real-world structures—hills, valleys, mountains, canyons, etc.—that they represent. Students can be helped to learn this correspondence if they are given 3-D versions of topographic maps (Rapp et al., 2007; Steinwand, Davis, & Weeks, 2002). By representing the landscape in a format that captures similarity at the level of object appearance, the 3-D map can help the student establish the correspondences between a topographic map and the landscape. Further, there is evidence that this "easy alignment" helps students go on to do the more difficult alignment of a standard topographic map and a landscape. Rapp et al. (2007) found that students who received 3-D maps were subsequently better able to use a standard topographic map to imagine themselves in the environment and to make route perspective judgments.

v. Alignment and contrast. As noted above, another use of close similarity is to create a focused contrast. A good way to highlight a particular aspect of a situation is by arranging a comparison with another situation that is identical *except* for that feature. This technique can be used to teach students to students to discriminate between similar structures (e.g., faults vs. fractures; see Figure 2) or categories (e.g., normal vs. reverse faults; Figure 3). Another application, often used in geoscience textbooks (e.g., Grotzinger et al., 2007; Marshak 2005; Reynolds et al., 2007;), is to present images that represent two or more discrete states of a dynamic process, such as seafloor spreading, erosion, glaciations, etc. When each state is depicted in a similar fashion, comparison is facilitated, and the student may be better able to detect the relevant changes that occur over time. In fact, presenting a series of comparable static images can be equally or sometimes more effective than presenting animations (e.g., Tversky, Morrison, & Bétrancourt, 2002). In an animation, the information may move too fast, and the viewer can miss the key changes. However, a good set of static images remains available for comparison, and highlights the relevant differences between them.

FUTURE WORK AND CONCLUSIONS

In sum, analogy is a powerful tool in teaching geoscience. While geoscience teachers have long understood this power, this paper places the use of analogy in a theoretical framework that provides insights into when and why a particular analogy might work. By thinking explicitly about the structural relationships between the source and the target, the surface similarity, the goals of the analogy and its limits, teachers can anticipate whether or not an analogy is going to have the desired impact on students' understanding. Effective analogies for novice students tend to involve examples for which: (1) the correct knowledge is readily retrieved and (2) corresponding elements in the source and target are relatively easy to align; and (3) the two examples are sufficiently different that the common system stands out (always provided that condition (2) is met). In the case of projective analogy, a further desideratum is that a number of useful inferences are possible. In the case of mutual alignment analogy, the common system highlighted (and any contrasts highlighted) should be of instructional importance.

By considering the roles of analogies, including those that use physical models, we can expand our use of analogy, make explicit to students the role that analogies are playing in their learning, and help them develop general expertise on the use of analogy to learn. Finally, theory and research in cognitive science suggest a number of specific, practical steps that teachers can take to maximize the usefulness of analogy in student's learning.

While this paper lays out an initial framework for thinking about the use of analogies in gesocience teaching and learning, analogies are such a fundamental part of geoscience teaching that additional work in this area would likely yield substantial benefits. For one, it would be valuable to observe how instructors use analogies in teaching geoscience. In light of the issues discussed here, what techniques do instructors actually implement in their classrooms? How do they do so? What techniques are seldom applied, and why? A better understanding of the use of analogy in geoscience lectures, laboratories, and field exercises would support the design and implementation of further instructional supports, and shed light on unforeseen issues related to the use of analogy in geoscience. Another interesting area of research concerns experts' mental representations. The present paper has focused on how initial learning can be supported through analogy, but it is also interesting to consider how analogical learning relates to additional learning experiences. As a student gains expertise in a topic, do the initially useful analogies remain stored in memory? Are they changed, discarded, or integrated with additional knowledge? Although the long-term influence of analogical instruction has received little research attention, it would provide valuable insights for education. It is our belief that further collaborations between cognitive scientists and geoscience instructors will pave the way to new insights about analogical thinking in this complex, challenging domain, and contribute further enhancements to geoscience instruction.

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REFERENCES

Baker, D. R., Dalpé, C., and Poirier, G., 2004, The viscosities of foods as analogs for silicate melts: Journal of Geoscience Education, v. 52, p. 363-367.

Benison, K. C., 2005, Artificial outcrops give real experience in interpreting a geologic history: the CMUland group project for historical geology courses: Journal of Geoscience Education, v. 53, p. 501-507.

Chandler, P., and Sweller, J., 1991, Cognitive load theory and the format of instruction: Cognition and Instruction, v. 8, p. 293-332.

Chi, M. T. H., Feltovich, P. J., and Glaser, R., 1981, Categorization and representation of physics problems by experts and novices: Cognitive Science, v. 5, p. 121-152.

Clement, J., 1993, Using bridging analogies and anchoring intuitions to deal with students' preconceptions in physics: Journal of Research in Science Teaching, v. 30 no. 10, p. 1241 1257.

Clement, J., 1998, Expert novice similarities and instruction using analogies: International Journal of Science Education, v. 20, p. 1271-1286.

Crouch, C. H., Fagen, A. P., Callan, J.P. and Mazur, E., 2004. Classroom demonstrations: Learning tools or entertainment?: American Journal of Physics, v. 72 no. 6, p. 835–38.

Falkenhainer, B., Forbus, K. D., and Gentner, D., 1989, The structure-mapping engine: Algorithm and examples: Artificial Intelligence, v. 41, p. 1-63.

Francek, M. A., and Winstanley, J. D. W., 2004, Using food to demonstrate earth science concepts: a review: Journal of Geoscience Education, v. 52, p. 154-160.

Gates, A. E., 2001, Hands-on exercise in environmental structural geology using a fracture block model: Journal of Geoscience Education, v. 49, p. 443-449.

Gentner, D., 1983, Structure-mapping: A theoretical framework for analogy: Cognitive Science, v. 7, p. 155-170.

Gentner, D., 1989, The mechanisms of analogical learning: In S. Vosniadou, and A. Ortony (Eds.), Similarity and analogical reasoning: London, Cambridge University Press, p. 199-241.

Gentner, D., 2005, The development of relational category knowledge: In L. Gershkoff-Stowe and D. H. Rakison, (Eds.), Building object categories in developmental time: Hillsdale, Erlbaum, p. 245-275.

Gentner, D., and Colhoun, J., Analogical processes in human thinking and Learning: In A. von Müller and E. Pöppel (Series Eds.) and B. Glatzeder, V. Goel, and A. von Müller (Vol. Eds.), On Thinking: Vol. 2. Towards a Theory of Thinking: Springer-Verlag, Berlin Heidelberg. (in press).

Gentner, D., and Clement, C., 1988, Evidence for relational selectivity in the interpretation of analogy and metaphor: In G. H. Bower (Ed.), The psychology of learning and

motivation: Advances in research and theory, v. 22: New York, Academic Press, p. 307-358.
Gentner, D., and Gentner, D. R., 1983, Flowing waters or teeming crowds: Mental models of electricity: In D. Gentner and A. L. Stevens (Eds.), Mental models: Hillsdale, Lawrence Erlbaum Associates, p. 99-129.
Gentner, D., and Kurtz, K., 2006, Relations, objects, and the composition of analogies: Cognitive Science, v. 30, p. 609-642.
Gentner, D., Loewenstein, J., and Hung, B., 2007, Comparison facilitates children's learning of names for parts: Journal of Cognition and Development, v. 8, p. 285-307.
Gentner, D., Loewenstein, J., and Thompson, L., 2003, Learning and transfer: A general role for analogical encoding: Journal of Educational Psychology, v. 95 no. 2, p. 393-408.
Gentner, D., and Markman, A. B., 1994, Structural alignment in comparison: No difference without similarity: Psychological Science, v. 5, p. 152-158.
Gentner, D., and Markman, A. B., 1997, Structure mapping in analogy and similarity. American Psychologist, v. 52, p. 45-56.
Gentner, D., and Namy, L., 1999, Comparison in the development of categories. Cognitive Development, v. 14, p. 487-513.
Gentner, D., and Sagi, E., 2006, Does "different" imply a difference? A comparison of two tasks, in Proceedings, R. Sun and N. Miyake (Eds.): Twenty-eighth Annual Meeting of the Cognitive Science Society, Vancouver: BC, p. 261-266.
Gentner, D., and Toupin, C., 1986, Systematicity and surface similarity in the development of analogy, Cognitive Science, v. 10, p. 277-300.
Gick, M. L., and Holyoak, K. J., 1983, Schema induction and analogical transfer. Cognitive Psychology, v. 15, p. 1-38.
Goldstone, R. L., and Medin, D. L., 1994, Time course of comparison: Journal of Experimental Psychology: Learning, Memory and Cognition, v. 20 no. 1, p. 29-50.
Grotzinger, J., Jordan, T. H., Press, F., and Siever, R., 2007, Understanding Earth, 5th Edition: New York, W. H. Freeman, 672 p.
Halpern, D. F., Hansen, C., and Riefer, D., 1990, Analogies as an aid to understanding and memory: Journal of Educational Psychology, v. 82, p. 298–305.
Harrison, A. G., and Coll, R. K., 2008, Using analogies in middle and secondary science Classrooms: Thousand Oaks, CA., Corwin Press.
Harrison, A. G., and Treagust, A. G., 1993, Teaching with Analogies: A Case Study in Grade-10 Optics: Journal of Research in Science Teaching, v. 30, p. 1291-1307.
Hermann, R., and Lewis, B., 2004, A formative assessment of geologic time for high school earth science students: Journal of Geoscience Education, v. 52, p. 231-235.
Holyoak, K. J., and Koh, K., 1987, Surface and structural similarity in analogical Transfer: Memory & Cognition, v. 15, p. 323-340.
Holyoak, K. J., and Thagard, P. R., 1989, Analogical mapping by constraint satisfaction: Cognitive Science, v. 13, p. 295-355.
Hammer, R., Diesendruck, G., Weinshall, D., and Hochstein, S., 2009, The development of category learning strategies: What makes the difference?: Cognition, v. 112, p. 105-119.
Iding, M. K., 1997, How analogies foster learning from science texts: Instructional Science, v. 25, p. 233–253.
Jee, B. D., Uttal, D., & Gentner, D., 2008, To find *fault* is easy? The role of comparison in learning a geological structure, in Proceedings, B. C. Love, K. McRae, & V. M. Sloutsky (Eds.): Thirtieth Annual Conference of the Cognitive Science Society, Washington: DC, p. 1219.
Jee, B. D., and Wiley, J., 2007, How goals affect the organization and use of domain Knowledge: Memory & Cognition, v. 35, p. 837-851.
Johnson-Laird, P. N., 1983, Mental models: Cambridge, Harvard University Press.
Joshua, H., and Dupin, J. J., 1987, Taking into account student conceptions into an instructional strategy: An example in physics: Cognition and Instruction, v. 4, p. 117–135.
Jones, M., and Love, B. C., 2007, Beyond common features: The role of roles in determining similarity: Cognitive Psychology, v. 55, p. 196–231.
Kastens, K. A., Agrawal, S., and Liben, L.S., 2008, Research in science education: The role of gestures in geoscience teaching and learning: Journal of Geoscience Education, v. 56, p. 362-368.
Kastens, K. A., and Rivet, A., 2008, Multiple Modes of Inquiry in Earth Science: Science Teacher, v. 75 no. 1, p. 26-31.
Keane, M. T., 1996, On adaptation in analogy: Tests of pragmatic importance and adaptability in analogical problem solving: The Quarterly Journal of Experimental Psychology, v. 49 no. 4, p. 1062-1085.
Kotovsky, L., and Gentner, D., 1996, Comparison and categorization in the development of relational similarity, Child Development, v. 67, p. 2797-2822.
Krawczyk, D., Holyoak, K., and Hummel, J., 2004, Structural constraints and object similarity in analogical mapping and inference: Thinking and Reasoning, v. 10, p. 85-104.
Kurtz, K. J., Miao, C., and Gentner, D., 2001, Learning by analogical bootstrapping: Journal of the Learning Sciences, v. 10 no. 4, p. 417-446.
Libarkin, J. C., Anderson, S. W., Dahl, J., Beilfuss, M., and Boone, W., 2006, Qualitative analysis of college students' ideas about the Earth: Interviews and open-ended questionnaires: Journal of Geoscience Education, v. 53, p. 17-26.
Markman, A. B., 1997, Constraints on analogical inference: Cognitive Science, v. 21, p. 373–418.
Markman, A. B., and Gentner, D., 1993, Structural alignment during similarity Comparisons: Cognitive Psychology, v. 25, p. 431-467.
Markman, A. B., and Gentner, D., 1996, Commonalities and differences in similarity Comparisons: Memory & Cognition, v. 24, p. 235-249.
Marshak, S., 2005, Earth: portrait of a planet: New York, W. W. Norton and Company, 735 p.
McPhee, J., 1981, Basin and range: New York, Farrar, Straus, and Giroux, 216 p.
Orgill, M. K., and Bodner, G. M., 2006, An analysis of the effectiveness of analogy use in college-level biochemistry textbooks: Journal of Research in Science Teaching, v. 43, p. 1040–1060.
Posner, M. I. and Keele, S. W., 1968, On the genesis of abstract ideas: Journal of Experimental Psychology, v. 77, p. 353–363.
Rapp, D. N., Culpepper, S. A., Kirkby, K., and Morin, P., 2007, Fostering students' comprehension of topographic maps: Journal of Geoscience Education, v. 55, p. 5-16.
Reynolds, S., Johnson, J., Kelly, M., Morin, P., and Carter, C., 2007, Exploring Geology: New York, McGraw-Hill, 624 p.
Richland, L. E., Zur, O., and Holyoak, K. J., 2007, Cognitive supports for analogies in the mathematics classroom: Science, v. 316, p. 1128-1129.
Ross, B. H., 1987, This is like that: The use of earlier problems and the separation of similarity effects: Journal of Experimental Psychology: Learning, Memory, and Cognition, v. 13 no. 4, p. 629-639.
Ross, B. H., 1989, Remindings in learning and instruction: In S. Vosniadou and A. Ortony (Eds.), Similarity and analogical reasoning: New York, Cambridge University Press, p. 438-469.

Sibley, D., 2009, A cognitive framework for reasoning with scientific models: Journal of Geoscience Education, v. 57, p. 255-263.

Steinwand, D., Davis, B., and Weeks, N., 2002, Geowall: Investigations into low-cost stereo display systems: USGS Open File Report 03-198.

Sweller, J., 1988, Cognitive load during problem solving: Effects on learning: Cognitive Science, v. 12, p. 257-285.

Taber, K. S., 2001, When the analogy breaks down: Modeling the atom on the solar System: Physics Education, v. 36, p. 222-226.

Thagard, P., 1992, Analogy, explanation, and education: Journal of Research in Science Teaching, v. 29, p. 537-544.

Tolley, S. G., and Richmond, S. D., 2003, Use of the lava lamp as an analogy in the geoscience classroom: Journal of Geoscience Education, v. 51, p. 217-220.

Treagust, A. G., 1993, The evolution of an approach for using analogies in teaching and learning science: Research in Science Education, v. 23, p. 293-301.

Truscott, J. B., Boyle, A., Burkill, S., Libarkin, J., and Lonsdale, J., 2006, The concept of time: can it be fully realised and taught?: Planet, v. 17, p. 21-23.

Tversky, B., Morrison, J. B., and Bétrancourt, M., 2002, Animation: can it facilitate?: International Journal of Human –Computer Studies, v. 57, p. 247–262.

Wagner, J. R., 1987, Using layer-cake geology to illustrate structural topographic Relationships: Journal of Geoscience Education, v. 35, p. 33-36.