A COGNITIVE FRAMEWORK FOR REASONING WITH SCIENTIFIC MODELS

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ABSTRACT

Humans reason by analogy (Lakoff and Johnson, 1980; Gentner, 1983; 2003; Hofstadter, 2001, 2006; Pinker, 2007). Some have further argued that analogs can be scientific models (Hesse, 1966, Clement, 1989) although clearly not all analogies are models. Analogies based on mere physical similarity are not equivalent to scientific models but analogies based on shared relationships between the analog and target maybe equivalent to scientific models. A literature review of analogies and scientific models indicates that all scientific models in geology are relational analogs. Relational analogs are equivalent to models because both: 1) are based on recognizing relational characteristics of the analog (or model) and target, 2) map similarities and differences between the analog (or model) and target and 3) support inferences about the target based on relational similarities between the target and analog (or model). Therefore, the cognitive processes involved in analogical thinking provide a theoretical, research-based framework for instruction designed to improve students' ability to learn how to use and generate scientific models.

INTRODUCTION

Libarkin et al. (2003, p. 121) noted, "Debate over the thought processes and cognition of individuals encountering new information, especially scientific information, is an important component of science education discourse. Researchers are primarily interested in whether learners use models and how they use them." This paper is intended to be a contribution to that debate. I argue that the cognitive processes involved in thinking and reasoning with analogies are the same as those involved in thinking and reasoning with scientific models.

This argument is based on two theses. The first thesis, based on a review of work by cognitive scientists, is that people naturally use analogies to explain phenomena. The second, and primary thesis of this paper is that geoscientific models are constructed by building relational analogies. This thesis has not been argued in previous geoscience literature, although philosophers (Frodeman, 1995) and geoscientists (Schumm, 1991) have noted that geoscientists frequently reason by analogy. If these two theses are correct, then the large body of cognitive science research on analogical reasoning provides a theoretical basis for instruction designed to help students understand and develop scientific models, particularly in the geosciences.

The ability to use and generate models of scientific phenomena is a key component of scientific literacy (Clement, 2000; Gobert and Buckley, 2000; Coll, 2005). White and Frederiksen (1998) argue that students' lack of understanding of how to build scientific models is one of the main reasons students have difficulty learning science. Project 2061, a long-term effort by the American Association for the Advancement of Science to support scientific literacy for all citizens, similarly recognizes students need to learn how to construct scientific models to truly learn science (AAAS, 1993). Another attempt to promote scientific literacy, the National Research Council (NRC, 2000) encourages instructors to adopt inquiry-based pedagogies that provide students authentic experience in scientific reasoning. Whether or not inquiry, as done in many school settings, helps students understand and use scientific models is debatable (Winschitl et al., 2008), especially as inquiry is often implemented with students who test models that they do not understand. If students are to participate in the process of reasoning with scientific models, teachers and students must understand how scientists use and create scientific models. Simply presenting students with models or asking students to create their own models may not be adequate. Scientific models are complex representations and may be best learned and understood by students if they recognize and practice the cognitive processes involved in creating and understanding analogies.

SCIENTIFIC MODELS

The term model is used very broadly within and outside science (e.g., Gilbert 1991; Libarkin et al., 2003) to describe a variety of types of representations. Scientific models (see Table 1, Definitions of terms) are representations shared by experts to make predictions or retrodictions about concepts, objects, systems, data, processes or events. These representations may be verbal, diagrammatic, physical and/or mathematical. This definition agrees with variations presented by science educators (e.g. Gilbert, 1989; Gilbert and Boulter, 1997; Gobert and Buckley, 2000; Windschitl et al., 2008) with the addition of the term retrodiction, an important aspect of geological reasoning.

Van Driel and Verloop's (1999) review of the history and philosophy of science literature and science education literature led them to recognize seven characteristic features of scientific models (Table 2). In a follow up study, Van Der Valk et al. (2007) demonstrated that scientists' own perceptions of the meaning of "model" as a scientific concept fit these seven characteristics. They used a survey with 10 statements about scientific models and asked the scientists to choose whether or not each statement accurately represented how they used scientific models in their own work. The result of the survey, with 24 respondents, is consistent with the characteristics listed in table 2. Two of the statements referred to the idea that scientists use models because they are more accessible

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TABLE 1. DEFINITIONS OF TERMS

Relational Analog- an object, event, process, phenomenon or concept that shares relational similarities with another.
Relational Analogy- a comparison between objects, events, processes, phenomena or concepts that shares relational similarities with one another.
Domain- an area of knowledge represented by a set of similar and/or related concepts
Elements- concepts, objects, systems, data, processes or events.
Exemplar- a typical instantiation an object, event, process, phenomenon or concept.
Mapping- process of comparing and contrasting characteristics of the analog and target
Mental model- a personal mental representation, typically used to reason, act or plan.
Normic statements- generalizations that permit exceptions. For example, beach sands tend to be better sorted than fluvial sands.
Prototype- a hypothetical representation of a category that emphasizes distinguishing characteristics and/or central tendencies.
Retrieval- noticing some features of the target that may be represented by the analog
Target- an object, event, process, phenomenon or concept that an analog may represent.
Transfer- applying knowledge to a new situation.
Retrodiction- inference about past events.
Schema- a distinct mental representation that can be held in working memory and used to categorize objects, events, processes, phenomena or concepts
Scientific model- a representation used by experts to make predictions or retrodictions about concepts, objects, systems, data, processes or events
Similarity– resembles but is not identical. Similarity is more general than analogy because it includes characteristics that are not relational such as my red shirt is a similar color to a robin's breast.
Source- synonym of analog, also referred to as a base.

than the target. One of the statements refers to the ability to manipulate the model. For example, one can change parameters in a mathematical model of atmospheric circulation and monitor effects on some aspects of the output whereas one cannot actually change atmospheric circulation. Accessibility may also refer to physical or temporal proximity because closer proximity may allow one to recognize more characteristics of the model. For example, modern fluvial deposits on Earth serve as models for ancient sediments on Mars inferred to be fluvial deposits. In a third study of scientists' views of the characteristics of models, Schwartz and Lederman (2005) interviewed and surveyed 24 active research scientists in tenured academic positions. The most commonly stated view among the scientists (17 out of 24) is that models help explain or organize observations and may be used for making predictions and testing. This is consistent with statement 7 (Table 2).

Although scientists create models based on empirical understanding of natural phenomena, models are by their nature imperfect representations. In turn, scientists must judge the value of predictions (or retrodictions) about future (or past) events made with these imperfect models. In the case of climate prediction, the Intergovernmental Panel on Climate Change concludes that uncertainties in model predictions are based on expert judgment rather than formal probabilistic methods (Christensen et al., 2007). Schwartz and Lederman (2005) queried scientists about their use of models and found expert judgment, not rigorous logic is used to determine how well models work. An atmospheric scientist stated, "*The model is scientific because its predictions can be verified quantitatively by peers*" (Schwartz and Lederman 2005, p. 7). This statement might lead one to conclude that evaluating predictions of the model in question is rigorous by standards of a formal logic. However, the scientist goes on to state *"You have to model what is happening on the average over the whole cloud. ...You are probably aware that the treatment of clouds in climate models is one of the weakest links in the chain of things that we need to put together to say something sensible about global warming. And we don't do it very well. The models are all over the map, depending on how they parameterize the cloud process"* (Schwartz and Lederman 2005, p. 7). Clearly, quantitative prediction does not equal accurate prediction to this scientist. The following statements from a "News and Reviews" article in *Nature* are a good example of the rationale involved in evaluating predictions from a model. The paper referred to in the statements is a report of an attempt to model effects of elevated atmospheric CO_2 on global runoff.

"*Using a technique known as 'optimal finger printing'…,Gedney et al. show that this direct effect of elevated CO_2 on plant transpiration is the dominant contributor to observed increases in continental runoff. Optimal fingerprinting is simply a statistical regression in which a model simulation is compared with the observed data... The authors' analysis shows that the model-simulated runoff trends are consistent with the observed trend only when the direct effect of CO_2 on transpiration is included in the simulation'.*

'As with any statistical analysis, these results are only as sound as the model used, the experimental design and the quality of observations. As our understanding of the terrestrial biosphere and our ability to model it improves, contributors to observed runoff trends that were not considered in this study may well be identified." (Matthews, 2006, p. 794).

The second paragraph points out that statistical analysis alone is inadequate to determine exactly what one may infer based on similarities between observed data and the model simulation. An improved model, better observational data and inclusion of variables not considered in the original study might lead to different results.

The preceding examples suggest that model predictions contain an uncertainty that must be evaluated

TABLE 2.

MODEL CHARACTERISTICS[1]	ANALOGY CHARACTERISTICS[2]
1. A model has a target, which some object, event process, phenomenon or concept that it represents.	An analog has a target, which is some object, event process, phenomenon or concept that it represents.[3]
2. A model provides a means to gain information about the target that cannot be easily observed or directly measured.	Analogies are often used in science to explain characteristics of a target that cannot be directly observed (Duit, 1991).
3. A model cannot directly interact with the target.	An analog is different from the target.[3]
4. A model is, in some ways, analogous to a target and therefore allows one to construct hypothesis.	Evaluation of an analogy involves making tentative hypotheses based on the similarities between the target and analog (Genter and Colhoun, in press).
5. Models involve simplifications and interpretations that make them inexact representations of the target.	Analogy shares a common pattern of relationships among elements even though the elements of the target and analog differ (Holyoak, 2005).
6. Models are designed by compromise between analogies (similarities) and differences between model and target.	When drawing analogies, one pays attention to relevant similarities and differences (Gentner, 1983).
7. A model evolves through the process of using it to understand the target.	Evaluation of the analogy leads to abstraction and re-representation of the analog (Gentner, 2003).
8. A model helps explain or organize observations.	Evaluation of analogies is drawn to afford inferences (Gentner, 2003).
9. A model may be used for making predictions and testing.	Analogical reasoning leads to plausible inferences about the target (Holyoak, 2005).

[1]Left column is seven characteristics of scientific models (rows 1-7) from Van Driel and Verloop (1999) plus two additional characteristics (rows 8 & 9) from Schwartz and Lederman (2005).
[2]The right column is a list of comparable characteristics ofanalogies.
[3]The top and third rows in the analogy column is characteristics that follow directly from the definition of analogy.

by expert judgment. Use of judgment when comparing models is apparent in a quote from another scientist; "*It [a model] is a mental or physical construct. …If they (*model and target*) are similar, then that tells us there is a good chance the ideas that went into making the model are actually pretty good at representing what is going on in reality*" (Schwartz and Lederman 2005, p. 7).

In summary, scientific models are representations of natural phenomena accepted by a community of experts that share similarities with a target and allow one to make testable predictions or retrodictions about the target. The characteristics apply to verbal, diagrammatic, physical and/or mathematical scientific models (Van Driel and Verloop, 1999, Schwartz and Lederman, 2005, Van Der Valk et al., 2007). Expert judgment is required to evaluate how well the characteristics of the model match the characteristics of the target.

ANALOGS

"*Hume declared and Mill said much the same thing, that all reasoning whatsoever depends on resemblance or analogy, and the power to recognize it.*" *(Thompson, 1917)*

According to linguists and cognitive scientists, the human mind specializes in producing analogies (Lakoff and Johnson, 1980; Hofstadter, 2001; Pinker 2007). Scientists do it (Schumm, 1991; Brookes and Etkina, 2007); even children do it (Goswami, 2001). A young child easily draws the relational analogy between a bird nest and their own house despite the fact that more physical differences exist than similarities. Douglas Hofstadter (2007, p. xviii) writes in the preface to his recent book, *I Am A Strange Loop*, "*the bottom line is, every thought herein could be listed under analogies*." Part of the reason Hofstadter and many other cognitive scientists (e.g., Gick and Holyoak, 1983; Blanchette and Dunbar, 2002; Gentner, 2003; Holyoak, 2005) believe analogy is a fundamental cognitive process is that drawing analogies requires some sort of similarity mapping of one concept onto another. Similarity mapping is a component of induction and drawing a relational analogy is a special case of inducing based on relational similarities. Another argument for the centrality of analogical reasoning in human reasoning is that metaphors, which are linguistically embedded analogies, are pervasive in language (Lakoff and Johnson, 1981). The words "centrality" and "embedded", in the previous sentence, are common metaphors whose analogical basis has been subsumed in everyday thought and language.

Multiple definitions of the term "analogy" are a part of the common vernacular and scientific discourse. Clement (1989) distinguished "decorative" analogies that may enliven discourse from predictive analogies that he equated with scientific models. In biology, the term analogy may be used to describe organs with similar function that evolved differently. In this paper, *relational analogy* is defined as a pattern of shared relationships among elements in the target and analog even though many elements of the target and analog differ (Hoyloak, 2005; see Table 1 for definitions of terms). Relational analogies are synonymous with Clement's (1989) redictive analogies. Relational analogies differ from other types of similarity in that they are based on relationships that may include but are not limited to physical attributes. The similarity of relationships between the target and analog make relational analogs and scientific models equivalent because relationships reveal underlying processes or causation. A red shirt and a red stop sign are merely similar in color and this similarity does not suggest any relationship between the color of the shirt and any other characteristics. However, the color of the shirt and stop sign could be relational if the red shirt causes people to stop and notice, in which case, the behavior it elicits is analogous to a stop sign. This simple example demonstrates that the difference between relational analogy and other types of similarity (Table 3) is context dependent. Most importantly, while mere similarity is usually based on comparisons of physical characteristics, a comparison based on physical characteristic may be relational when scientists are attempting to discover physical characteristics that reflect meaningful relationships. The mere similarity in the color of halite and quartz is almost always irrelevant to geoscientists whereas the cubic arrangement of atoms in halite is commonly used as an analog for more complicated regular geometric patterns found in quartz and other minerals. The important relational characteristic underlying the geometric pattern is the bond energies of the lattice and attendant behaviors and properties.

Exemplars and prototypes can be relational analogs. Cartoonists use prototypical features to define characters. For example, Mickey Mouse evolved to appear to be a younger character when Walt Disney shortened his snout and enlarged his eyes because infants have prototypically smaller noses and larger eyes than adults. The physical attributes of the evolved Mickey suggested behavioral (e.g. relational) characteristics of the newer Mickey. A drawing of a halite cubic lattice functions as a prototypical relational analog for more complex lattice structures because one can use this simple lattice to explain features such as crystal morphology and cleavage in a more complex crystal system. Exemplars may also be cases of mere similarity or serve as relational analogs. An example of an exemplar serving as a relational analog is a dislocation in an actual halite lattice that results in spiral growth, which can serve as an analog for relationally similar dislocations leading to spiral growth in more complex lattices.

Reasoning and knowledge building through analogy use are well understood by cognitive scientists. Gentner (2003) and Gentner and Colhoun (in press) recognize five cognitive processes people use when they generate analogies (Table 4). Holyoak (2005), using different terminology (see Table 4), has similarly suggested a model for how these five processes result in learning (Figure 1). **Retrieval** is the process in which a current situation reminds someone of a prior situation. Most retrievals are quite mundane: a boiling kettle reminds us of another boiling kettle (Forbus et al., 1995). Occasionally retrieval provides the spark of genius we associate with development of a novel analogy. **Mapping** is the process whereby the analog and target are aligned and specific commonalities and differences emerge (Gentner and Markman, 1997). Mapping is where reasoning intersects with content knowledge. One must know or learn characteristics of the target and analog before one can meaningfully compare similarities and differences. **Evaluation** is the critical examination of the

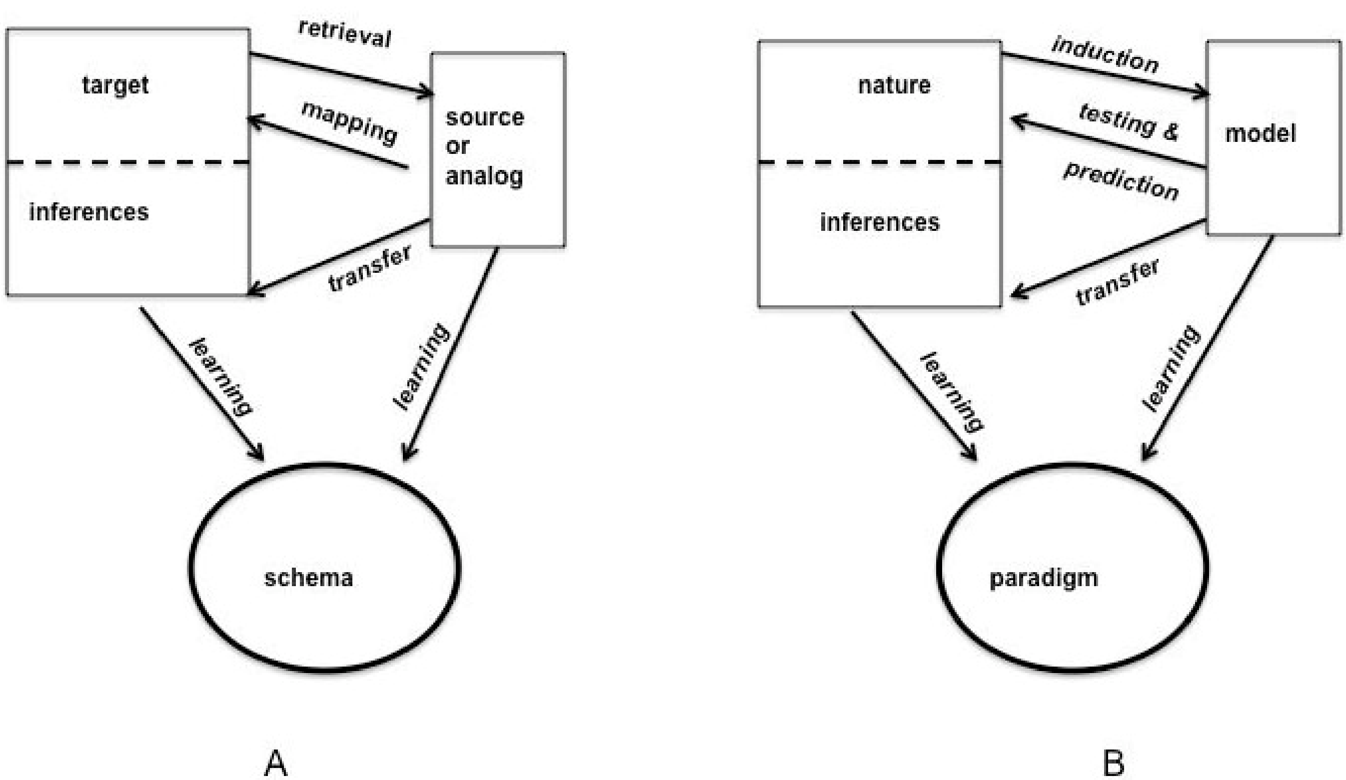

FIGURE 1. A) Diagram representing reasoning by analogy from Holyoak (2005) and B) a parallel representation of reasoning with scientific models.

TABLE 3. ANALOGY AND OTHER TYPES OF SIMILARITY[1]

TYPE OF SIMILARITY	DESCRIPTION	GEOLOGICAL EXAMPLE	REFERENCE
Relational Analog (relational similarity)	Involves a target that is to be explained or described, and a source that is already understood; can be based on relational matches and/or object matches between source and target.	Granite and gabrro could be categorized as analogical based on shared relations (igneous, intrusive).	Hummel and Holyoak, 2003
Prototype	Based on abstracted characteristics; is useful for categorization and for generating inferences about instantiations.	Sedimentology textbooks present prototypes and exemplars of sedimentary deposits formed in a variety of environment (e.g., beach, fluvial) that students are expected to be able to compare to the target.	Osherson and Smith, 1981
Exemplar	Exemplar of a category; otherwise similar in function to prototype	The type section of a formation.	Stoman and Ripps, 1989
Mere similarity (non-relational analog)	Similar in attributes but not relationally similar.	Granite and granite paragneiss have obvious similar appearance and could be categorized as mere similarity.	Gentner and Markman, 1997
Literal similarity	Similar in both attributes and relationally similar.	Granite and granodiorite share both attributes and relations (they are both igneous) and therefore could be characterized as literally similar.	Gentner and Markman, 1997
Metaphor	Linguistically embedded analogs.	The phrase heat flow refers back to the now defunct model of heat as a fluid.	Lakoff and Johnson, 1980

[1]Whether or not a statement falls into a specific category often depends on the context in which the statement is made.

commonalities and differences and, most importantly, the inferences afforded by an analogy. At least three criteria influence evaluation: (1) the structural consistency of the analogical mapping; (2) the plausibility of any new inferences in the target domain (for example, if the analogy makes an inference that is clearly false, this is reason to reject the analogy); and (3) the relevance of the inferences to the problem at hand (Gentner, 1989). When mapping occurs based on causal relationships, evaluation is equivalent to hypothesis testing. During evaluation one asks the question, "Does the presumed process which is active in the analog explain effects observed in the target?" When the process of evaluation is deemed successful, then the process of **abstraction** occurs because the causal principle becomes more generalized. Finally, **re-representation** occurs when evaluation and abstraction change the mental representation of the processes that affect the target and analog. For example, a student may have a very concrete mental representation of energy as the ability to do mechanical work, which may become more abstract and re-represented when the concept is expanded to include energy flow associated with chemical reactions. Learning includes, but is not limited to abstraction and re-representation.

COMPARING ANALOGIES AND MODELS

The terms model and analog are often used interchangeably by both scientists and educators (Hesse, 1966, 2000; Duit, 1991). Comparing analogs and models based on the preceding review of the characteristics of each suggests that this interchangeability is valid when analogies are based on relational characteristics. The term "representation" is used with respect to models and can be applied to analogs as well. Analogs can be individuals' representations as in mental models (Johnson-Laird, 2006) or a more public form of representations as in those presented in textbooks. The term "elements" refers to concepts, objects, systems, data, processes or events in both analogies and models. The only distinction between the definitions is the implication that scientific models are accepted by a community of experts whereas analogies may be less rigorously evaluated. Analogs based on mere similarity and relational analogs that are not accepted by a community of scientists are not equivalent to models, but relational analogs that are accepted by the community are equivalent to scientific models.

Comparisons can be drawn between Holyoak's (2005) model of reasoning by analogy and model-based reasoning in science (Figure 1). The following discussion of the cognitive processes will proceed step-wise but it is not intended to imply that people follow a step-wise path

TABLE 4. A COGNITIVE FRAMEWORK FOR REASONING ABOUT REALTIONAL ANALOGIES[1]

COGNITIVE PROCESSES (Gentner and Colhoun, in press)	EXPLANATION OF TERMS	HOYLOAK (2005)
Retrieval	A source (analog) similar to the target must be retrieved from long-term memory.	**Retrieval**
Mapping	Alignment of representational structures of the target and source to derive similarities and differences. This step includes making tentative inferences about the target based on the analog.	**Mapping**
Evaluation	Judgments are made about the usefulness and validity of the inferences that derive from the analogy.	**Transfer**
Abstraction	Development of generalizations about the category to which source and target belong.	**Learning**
Re-Representation	Alteration of the representation of either the source or the target to improve the usefulness of the analogy.	**Learning**

[1]Five cognitive processes involved in building an analogy (Gentner and Colhoun, in press) are defined. Comparable terms are used by Holyoak (2005) to describe learning by analogy. Similarities between relational analogies and scientific models suggests these same five processes apply to reasoning with scientific models.

when reasoning. Reasoning may be iterative and recursive (Hofstadter, 1979). One can start a description of the process of analogical reasoning with retrieval, the process of recognizing elements of a target that are similar those of a source. The parallel process in model-based reasoning is induction. Mapping in analogical reasoning is the process of articulating similarities and differences between the analog and target. Testing and predictions of models may lead to refinement of the model that improves the fit of the model with the process or object being modeled. Tests and predictions can also alter the model by drawing attention to other elements which, when incorporated into the model, may improve the fit. Transfer in analogical reasoning and in model-based reasoning is the process of drawing inferences about the target based on the analog or model. The goal of reasoning by analogy is to learn and the learning takes place in a constructivist framework of building on one's existing knowledge of the analog to better understand the target. This new knowledge can be though of as changing one's schema. In the case of models, schemas are similar to Kuhn's (1970) paradigms. Paradigm is used here in Kuhn's most frequently used sense of the term, an exemplary solution to a problem. The difference between schema and paradigm is that the former refers to a representation held by an individual and later refers to a representation held by a community.

Clear correlations between relational analogies and scientific models can be made. Ten statements about characteristics of analogies (right column, Table 2) parallel ten statements about scientific models that Vander Der Valk et al. (2007) used to characterize scientific models. I argue that this mapping indicates that relational analogs are synonymous with scientific models. In the next section, this argument will be tested through analysis of broadly accepted geologic models that are essentially analogs.

MODELS AND RELATIONAL ANALOGS IN GEOLOGY

Schumm (1991) states that analogy is the basis of geologic explanation and Frodeman (1995) argues that geologists reason by analogy, hypothesis and eliminative induction but neither author addresses the question of whether or not analogs and models are synonymous. When Lyell coined the geologists' premise, "the present is the key to the past", he tacitly expressed the central importance of drawing analogies in geological reasoning. Notice how, in the following statements, the terms model and analog could be used interchangeably. For example, Walther (1893) states, "the most satisfying genetic [genesis of] explanations of ancient phenomena were by analogy with modern geologic processes " (quote from Middleton 1973, p. 981). Airy (1855) describes the "perfect" analogy between the earth's crust floating on the mantle and a raft of timber floating on water. From pre-1900s scholars to modern texts, ice floating on water is also used as an analog for isostacy (Dutton, 1889; Sleep and Fujita 1997). Chamberlin and Salisbury (1907) use brittle deformation and plastic flow within glaciers as an analog for deformation of crustal and subcrustal rocks. In arguing for continental drift, Wegener (1924, in Oreskes, 1999) uses vertical crustal movement as an analog for lateral movement of the crust. He argues that if continental blocks can move vertically under the force of gravity, then surely (by analogy) they can move laterally. Analogies continue to remain prevalent in modern geoscience literature as demonstrated in a recent article published in EOS, *Brazilian Analog for Ancient Marine Environments on Mars* (Bridges et al., 2008).

Specific examples of models as analogs in sedimentology

A review of models listed in the index of the Encyclopedia of Sediments and Sedimentary Rocks (Middleton, 2003) shows that representations recognized as models by geoscientists have the characteristics of relational analogs. The encyclopedia was chosen for two reasons. First, because authors of articles in the encyclopedia were asked to provide reviews of accepted ideas, the models described within the encyclopedia can be assumed to be accepted by a large number of experts in the field. Second, I have sufficient expertise in sedimentology to understand construction and usage of the models in this domain. The models chosen for analysis are those listed under the term model in Middleton (2003). Nineteen of the 22 models listed in the index are distinct from each other with three others being three duplicates. Eight of the 19 distinct models are mathematical while the remaining eleven describe physical characteristics of earth materials. The various mathematical models generate data that can be compared to data gathered from measurements of physical attributes of the target. For example, some sediment transport models produce model grain size distributions that can be compared to grain size distributions of a real rock or sediment. Other models generate rates of sediment accumulation that can be compared to rates measured in natural deposits. Retrieval and mapping between target and model output (or analog) is relational because the features recognized in the target and described by the model are the result of processes that the model is designed to represent. The data pattern generated by the model can be compared to the data pattern in the target. Inferences are drawn by transfer (Figure 1) when the fit between the model or analog and target patterns are judged to be adequate. Whether or not the inferences are valid is a matter of judgment. Part of the judgment is based on how well patterns in the target and analog (or model) match. However, there are many other factors scientists must consider. Are there situations in which transferring the model or analog to the target results in obviously incorrect inferences? Are there important factors that the model or analog does not represent? Is there another model or analog that provides better results? All of these factors are determined by the collective judgments of experts in the field.

Qualitative descriptive models may be prototypical and exemplary descriptions to be compared to natural occurrences (target). Models of depositional environments of sedimentary rocks are exemplars and prototypes of sediments that accumulate in certain environments, such as rivers. The models (or relational analogs) are constructed by inferences of which features are most characteristic of river deposits. Because these analogs are used to distinguish sediments deposited in different environments, the choice of characteristic features must be based on observations of deposits formed by rivers as well as non-fluvial deposits from which one hopes to contrast the river deposits. Prototype and exemplar models include lists of physical characteristics and this could lead one to see these models as mere or literal similarities. However, expert sedimentologists recognize that physical characteristics of prototypes and exemplars serve as a basis for causal hydrodynamic interpretation (Walker, 1992) and, therefore, similarities between the model and target include relational (i.e. hydrodynamic) elements.

Models in the encyclopedia may also describe conditions that result in events. These models are not cause-and-effect deductive statements, but rather they are normic statements (Kitts, 1976; Schurz, 2001) of the sort wherein given A, B, C and D, E tends to occur. For example, descriptive models of dolomitization in the encyclopedia refer to different environments in which dolomite may form. For each environment, certain features such as crystal size, chemical composition of and spatial distribution of dolomite might be suggestive, but none of the features provide unequivocal evidence, of the origin of ancient dolomites. Researchers often conclude that a particular body of dolomite fits one model (analog) better than another by virtue of a qualitative mapping of analog and target characteristics. The mapping is qualitative even when quantitative reactive transport models are used to generate hypothetical distributions of dolomite (e.g. Jones and Xiao, 2005).

In summary, geologists often correctly use the terms model and analog interchangeably. Analogies based on carefully articulated relational similarities and differences between a target and analog that are accepted by a community of scientists are scientific models.

DISCUSSION AND IMPLICATIONS FOR INSTRUCTION

The first thesis of this paper, based on research in cognition is that learners, whether expert or novice, understand new information by drawing analogies to previous knowledge. One implication of this thesis is that instruction that builds on this general cognitive process can be successful in many knowledge domains. The second thesis of this paper is that all scientific models used by geoscientists are relational analogs (see Table 2 for a list of shared characteristics). The implication of this thesis is that scientific models are not special entities but rather a member of the broader class of cognitive representations referred to as analogies. Taken together, these theses imply that instructors can help students increase their ability to understand scientific models by taking advantage of the research on how people use analogies to learn (Figure 1). The five processes of analogical reasoning (Table 4) provide a research-based framework that educators can use to help students understand and generate scientific models.

Every new scientific concept students are exposed to offers an opportunity for students to practice analogical reasoning if instruction includes exercises designed to include the cognitive processes involved in reasoning about relational analogies. Because retrieval requires considerable knowledge of both the target and analog, it can be a barrier for novices. Therefore, in most situations, it is probably best if an instructor either presents an analog or guides students in analyzing an existing analogy. Instructors may then engage students in the process of mapping similarities and differences between an analog and target. During mapping, it is important to distinguish between relational and physical similarities and differences. The next process, evaluation, challenges students to draw inferences about the target. In many cases, novices will not have enough information about the target to know whether or not the inference they have drawn is valid. The instructor may either supply appropriate information or suggest students attempt to find ways to evaluate their inference. The processes of abstraction and re-representation follow successful evaluation and can be made apparent to the students by asking them to describe their understanding of the relational features before and after the exercise.

The bathtub as an analog for a reservoir in the hydrologic cycle provides a useful example of how one might guide students through an analogical reasoning exercise. A bathtub and a natural reservoir such as a lake share the physical characteristic of containing water. As soon as one adds a faucet and drain to the tub students may begin to explore relational similarities and differences based on processes affecting flux to and from the reservoirs. Students might then map a drain and faucet onto streams flowing into and out of a lake and relate fluxes in the bathtub and lake to gravitational potential. With or without prompting, students might recognize evaporation, precipitation and groundwater flow as additional fluxes associated with the natural reservoir. Students might evaluate the analogy by making predictions about how climate might drive changes in lake level and test the prediction with data from lakes in their area. Instructors may encourage the cognitive processes of abstraction and re-representation by challenging students to think of other natural reservoirs (e.g., oceans, atmosphere, glaciers, etc) and processes (groundwater flow, evapotranspiration, sublimation, etc.) that move water to and from those reservoirs. Instructors may also introduce additional concepts such as residence time and steady state, which the students may then map and evaluate. Once students have abstracted the analogy, they may then be challenged to retrieve a new analogy outside of the hydrologic cycle. Some may draw an analogy between reservoirs in the hydrologic cycle and those in the carbon cycle. Others might imagine a college as a reservoir of students with several fluxes in and out and a typical residence time.

Abstraction and re-representation would change the analog from a bathtub to something less concrete such as a box and arrow diagram with numerical values for reservoir sizes and fluxes. The representation can be made dynamic by representing fluxes mathematically and imposing constrains on reservoir sizes. Somewhere between the first iteration of a bathtub analog and a mathematical model of a system composed of multiple reservoirs and fluxes, the representation changes from an informal analog to a relational analog (i.e., scientific model). There is no exact transition point. Learning begins by recognizing mere similarity and continues at a more sophisticated and abstract level with the development of relational analogs that serve as scientific models.

Reasoning-by-analogy instruction may also address problems of students' non-scientific absolutist ("science is a bunch of facts to be learned") or radical relativistic ("science is just one of many equally valid ways of describing the world") epistemologies. Scientific reasoners are evaluativist who recognize scientific knowledge as human constructs and some constructs are more certain than others (Sandoval 2005, Kuhn et al. 2008). Practicing the process of evaluation, one of the five core cognitive processes in analogical reasoning, may help students recognize that to be a scientist means to investigate problems within a framework of reasoning.

Acknowledgments

This research was supported by NSF grant DUE-0243126. Julie Libarkin and Scott Clark provided discussion and criticism through out the project. Comments by an anonymous reviewer led to substantial improvements in the manuscript.

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