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The Role of Analogies in Chemistry Teaching

MaryKay Orgill
Department of Chemistry
University of Nevada, Las Vegas

George Bodner
Department of Chemistry
Purdue University

Abstract

Many chemistry *teachers* know that they can use analogies to help their students understand challenging or abstract information. Many chemistry *students*, on the other hand, know that analogies can generate a lot of confusion. In this chapter, we will discuss the potential advantages and disadvantages of using analogies in a chemistry classroom. We will also discuss three models that instructors can follow to use analogies effectively in their classes.

Biographies

MaryKay Orgill is an Assistant Professor of Chemistry at the University of Nevada, Las Vegas. Her education has been eclectic and her professional life somewhat schizophrenic so far. She studied chemistry at Brigham Young University to prove that a girl could "do chemistry" and do it well. She was surprised to find during her undergraduate studies that she actually liked chemistry—and loved teaching it. Not willing to be tied to only one kind of learning or working, she enrolled in graduate school at Purdue University to study both biochemistry and chemical education, completing a degree in each of those fields. She continued to pursue both interests as a first-year faculty member with a joint appointment in biochemistry and science education at the University of Missouri-Columbia. During that year, she took on the extra challenge (and incredible learning experience) of teaching a high school chemistry class. In 2004, she moved to her home state of Nevada to take a position at UNLV, where her research focuses on undergraduate chemistry and biochemistry education.

George Bodner is the Arthur E. Kelly Distinguished Professor of Chemistry, Education, and Engineering at Purdue University. He began his academic career as a history/philosophy major at the institution now known as the University at Buffalo. He found, much to his amazement, that chemistry was fun, and he changed his major under the mistaken impression that jobs were easier to find as a chemist. After a mediocre career as an undergraduate (B. S., 1969), he entered graduate school at Indiana University (Ph.D., 1972) where he apparently did well enough as a double major in inorganic and organic chemistry to gain an appointment as a visiting assistant professor at the University of Illinois (1972–1975). Two things became self-evident during his tenure at Illinois: he found that teaching was fun, and he realized that his research could best be described as searching for definitive answers to questions that no one ever asked. When the time came to leave Illinois, he therefore took a job as two-thirds of the chemistry faculty at Stephens College where he lasted for two years (1975–1977), teaching general, organic, inorganic, and biochemistry. He moved to Purdue University in 1977 to take a position in something known as "chemical education." He is the author of more than 100 papers and 45 books or laboratory manuals. His interests include the development of materials to assist undergraduate instruction, research on how students learn, and the history and philosophy of science. Last year, he was selected to receive the Nyholm Medal from the Royal Society of Chemistry, the Pimentel Award in Chemical Education from the American Chemical Society, and the Distinguished Alumni Award from his alma mater, the University at Buffalo.

Introduction

Whether we consciously realize it or not, analogy pervades our existence and our everyday reasoning. We live in a world of "perpetual novelty" (Gentner and Holyoak, 1997). No situation we encounter is exactly like a situation we have encountered previously, and our ability to learn and survive in the world is based on our ability to find similarities between past and present situations and use the knowledge we have gained from past situations to manage current situations. Analogy is powerful in that it allows us to create similarities for a variety of purposes, such as solving problems, creating explanations, or constructing arguments. In particular, an analogy's potential to make explanations of new material intelligible to students by comparing them to material that is already familiar makes analogy a powerful tool for educational purposes.

We've all sat in classes in which a teacher made a difficult or abstract concept understandable by using an analogy. Chemistry classes are full of abstract or challenging concepts that are not easy to understand unless they are related to something from our everyday experiences. For example, as the first author progressed through chemistry courses in her undergraduate studies, she found the concept of hybrid resonance difficult to understand. Her instructors would draw two different representations of benzene on the board, connected by double-headed arrows; this made her think that the resonance hybrid structure was alternating between two different forms. Fortunately, during one class period, an instructor compared a resonance hybrid to a mule. A mule is the product of a cross between a donkey and a horse, and, yet, it has its own unique characteristics. It is neither horse nor donkey, nor does it alternate between being a horse and a donkey. In the same way, a resonance hybrid can be thought of as the product of a cross between two resonance structures. The hybrid is neither of the two contributing structures, but a structure between that of the resonance structures and with its own unique characteristics. This analogy and other effective analogies clarify thinking, help students overcome misconceptions, and give students ways to visualize abstract concepts.

On the other hand, each of us has also sat in a class in which we did not understand an instructor's analogy. In the best-case scenario, we would ignore the analogy; it simply became a waste of class time. In the worst-case scenario, the analogy would confuse, mislead, or keep us from learning class material. While the first author was in graduate school, she was a teaching assistant for a general chemistry class. The instructor of the class had not taught undergraduates previously and, in an attempt to connect with the students on their level, used many analogies during class. Unfortunately, the students (and their teaching assistant!) did not understand these analogies. Their confusion about the analogies kept them from listening to and learning from the other information that was being presented in the class. Their weekly discussion periods were often spent relearning the concepts that they did not understand or could not focus on in the lecture. In this case, the analogies actually hindered learning.

The two chemistry instructors we have mentioned here were well intentioned. They both used analogies to help their students understand abstract and challenging concepts. However, one analogy was more effective than the other in helping students learn. What was the difference between the two? Is there a way to ensure that the analogies you use will be successful? While there is no way to guarantee that the analogies you use in your chemistry class will be understood by all of your students, there are some steps you can take to improve their effectiveness. First, though, you must understand what an analogy is, when analogies are useful in educational settings, and what the potential advantages and disadvantages of using an analogy are.

What Is an Analogy?

Simply put, an analogy is a comparison between two domains of knowledge—one that is familiar and one that is less familiar. The familiar domain is often referred to as the "vehicle," "base," "source," or "analog" domain; the less familiar domain, or the domain to be learned, is usually referred to as the "target" domain. This chapter will use the terms "analog" and "target," respectively, to refer to the two concepts or domains. For example, in many chemistry classes, providing the activation energy needed in order for a reaction to occur is compared to pushing a ball up one side of a hill before letting it roll down the other side. In this example, the person pushing the ball up the hill is the analog concept and activation energy is the target concept. Similarly, in biochemistry textbooks, the enzyme/substrate interaction is compared to placing a key in a lock, where the enzyme/substrate interaction is the target concept and the placement of the key in the lock is the analog concept.

To say that an analogy is a comparison may be an oversimplification. An analogy is not just a comparison between different domains: it is a special kind of comparison that is defined by its purpose and by the type of information it relates. According to Gentner (1989), an analogy is a mapping of knowledge between two domains such that the system of relationships that holds among the objects in the analog domain also holds among the objects in the target domain. Thus, the purpose of an analogy is to transfer a system of relationships from a familiar domain to one that is less familiar (Mason and Sorzio, 1996). The strength of an analogy, therefore, lies less in the number of features the analog and target domains have in common than in the overlap of relational structure between the two domains (Gentner, 1983). For example, the strength of the lock-and-key analogy for enzyme/substrate complementarity is not simply in the fact that the lock corresponds to the enzyme and the key corresponds to the substrate. The strength of that particular analogy is that the relationships between the lock and the key (for example, the shape of the key is complementary to the shape of the lock, and part of the key fits inside the lock) correspond to relationships between the enzyme and the substrate (the shape of the substrate is complementary to the shape of the enzyme, and part of the substrate fits “inside” the enzyme).

Are Analogies Beneficial in Educational Settings?

Very little research has been done about the use of analogies in chemistry classes, and the results of research on whether analogies are beneficial in science education are ambiguous (Beall, 1999). Many studies have reported that using analogies resulted in beneficial outcomes (Beveridge and Parkins, 1987; Brown and Clement, 1989; Cardinale, 1993; Clement, 1993; Donnelly and McDaniel, 1993; Fast, 1999; Glynn and Takahashi, 1998; Harrison and Treagust, 1993; Hayes and Tierney, 1982; Holyoak and Koh, 1987; Simons, 1984; Solomon, 1994; Treagust, Harrison, and Venville, 1996). In a study by Harrison and Treagust (1993), for example, a teacher explained what happens to light when it obliquely enters a more dense medium (refraction) by comparison with what happens to a set of Lego wheels when they roll, unaided, from a hard floor onto a carpeted surface. The trajectory of the light (wheels) is bent toward the normal as it passes through a more dense medium (the carpet) because the light (the wheels) slows down. After the instruction, the students were interviewed, and each seemed, in general, to understand the concepts being taught—both the analogical concept and the target concept in optics. In addition, most of the students were able to transfer their analogical reasoning to a completely new situation. They were able to correctly predict what will happen to light as it moves from a more dense medium to a less dense medium (it bends away from the normal).

Other studies have reported that the use of analogies has had little or no effect on learning (Bean, Searles, and Cowen, 1990; Friedel, Gabel, and Samuel, 1990; Gilbert, 1989). Friedel, Gabel, and Samuel (1990), for example, studied preparatory college chemistry students over the course of two years. Half of the students in their study were instructed with analogies in addition to the regular instruction. Students were given tests to rate their math anxiety, their reasoning abilities, and their visualization abilities.

At the end of the semester, each student took a final exam and a matching exam, in which students were asked to match chemical terms with their analogical corollaries. For example, the following matched questions compare the bags of oranges and moles of Neon:

> 1. How much would 120 oranges weigh? What would be the mass of 3.60×10^{24} atoms of Ne?
> 2. What is the weight of 4 bags of oranges? If you had 0.25 moles of Neon, what mass would you have? (Friedel, Gabel, and Samuel, 1990, p. 680).

There were no differences in the posttest scores of the two groups. However, scores on posttests showed that

> students in the treatment group who had high visualization skills were actually penalized by using analogs. The data analysis shows that these kinds of students became more successful problem solvers by solving additional practice problems rather than by using analogs. (Friedel, Gabel, and Samuel, 1990, p. 678)

There are two ways to explain why some studies suggest positive results when analogies are used while others show either no effect or a negative effect: analogies are only beneficial under certain circumstances or analogies are only useful for certain kinds of students.

Are Analogies Only Useful in Promoting Learning Under Certain Circumstances? Many reports indicate that analogies may only be useful for teaching target concepts that are conceptually difficult or abstract (Cardinale, 1993; Duit, 1991). If target concepts are relatively simple to understand, an analogy may not be necessary to explain the concepts. In fact, in that case, an analogy may be simply extra information for students to remember (Gick and Holyoak, 1983). In chemistry, however, where concepts are often novel and challenging or difficult to visualize, the use of analogies may have beneficial effects on learning (Harrison and Treagust, 1996).

There is also reason to believe that certain instructional criteria must be met in order for an analogy to be effective. Gabel and Samuel (1986), for example, found that analogies are most useful when students understand the analog domain well. In the case of Gabel and Samuel's article, the concentration of lemonade was compared to the concentration of other chemical solutions. Students were able to use the lemonade analogy to solve problems in which the concentration of a solution was changed by adding solvent because they had experienced diluting a strong lemonade drink by adding water. On the other hand, students did not find the lemonade analogy as useful when solving problems in which the concentration of a solution was changed by evaporating solvent because the students were not familiar with making a weak lemonade drink stronger by evaporating off some of the water.

Other researchers have suggested that effective use of analogies occurs when teachers explicitly compare analog and target domains and identify the limitations of an analogy (see Glynn, 1991; Treagust, 1993; Zeitoun, 1984). Teachers can even guide their students through the identification of these similarities and limitations. We have used this strategy in a high school chemistry class. The students were beginning a unit about chemical reactions and chemical equations, and we used an analogy that compared chemical equations to recipes to introduce the concepts. We gave the students a page on which we printed both a recipe and a chemical reaction and asked the students to identify the ways in which equations are similar to chemical recipes. They were able to identify several similarities, which each student noted on his or her own page; some of these similarities are as follows: (1) some equations have names and some recipes have names; (2) equations list reactants (chemicals that will be added together) and recipes list ingedients (foods that will be added together); (3) equations list the physical state of the reactants and recipes list the physical state of ingredients (mashed versus sliced, for example); and (4) equations list the conditions under which a reaction takes place and recipes list the conditions under which baking or cooking occurs. After we discussed the similarities between equations and recipes, we asked the students to identify the ways in which equations and recipes are different. They were able to determine that while recipes give the time needed for a recipe to be completed, chemical equations do not indicate how long a chemical reaction will take to occur. Because the students understood and wrote down the meaning of the analogy, they refered to the analogy during subsequent learning about chemical equations and reactions.

What Kind of Students Benefit from Analogies? The research literature suggests that not all analogies are useful analogies. Even a “good” analogy may not be useful for all students. Several studies suggest that analogies are more useful for low-ability students than for high-ability students (Bean, Singer, and Cowan, 1985; Donnelly and McDaniel, 1993; Duit, 1991; Gabel and Sherwood, 1980). Studies by Gabel and Sherwood (1980) and Donnelly and McDaniel (1993) indicated that instruction in analogies seemed to be more helpful for students of low formal reasoning ability and high mathematics anxiety than for more capable students because the achievement scores of students with lower formal reasoning ability changed more after analogy instruction than the achievement scores of students with higher ability.

The work which suggests that analogies are more useful for low-ability students could be deceiving, however. It is possible that no change was seen in the achievement scores of the high-ability students because their scores were closer to the maximum available score before instruction with analogies. It is also possible that the high-ability students had a good understanding of the material before analogy instruction, in which case instruction with analogies would not significantly improve their understanding of the concept.

Regardless of whether low-ability students are, in fact, helped more by analogies than high-ability students, there is evidence that some teachers believe this is the case and tend to use more analogies with students they consider to be of lower reasoning abilities. When student teachers were interviewed about their use of analogies, they indicated that they tended to use more analogies with students they perceived as having lower reasoning abilities than with students they perceived as having higher reasoning abilities (Jarman, 1996).

Whether an analogy is useful to a given student may also depend on the student’s familiarity with the topic being taught. Novick (1988) divided undergraduate students into groups of “experts” and “novices” according to their math SAT scores and gave them a target problem to solve:

> Members of the West High School Band were hard at work practicing for the annual Homecoming Parade. First they tried marching in rows of twelve, but Andrew was left by himself to bring up the rear. The band director was annoyed because it didn’t look good to have one row with only a single person in it, and of course Andrew

> wasn't very pleased either. To get rid of this problem, the director told the band members to march in columns of eight. But Andrew was still left to march alone. Even when the band marched in rows of three, Andrew was left out. Finally, in exasperation, Andrew told the band director that they should march in rows of five in order to have all the rows filled. He was right. This time all the rows were filled and Andrew wasn't alone any more. Given that there were at least 45 musicians on the field but fewer than 200 musicians, how many students were there in the West High school Band? (Novick, 1988, p. 513)

Half of the experts and half of the novices were also given an analogous problem that potentially could help them solve the target problem:

> Mr. and Mrs. Renshaw were planning how to arrange vegetable plants in their new garden. They agreed on the total number of plants to buy, but not on how many of each kind to get. Mr. Renshaw wanted to have a few kinds of vegetables and ten of each kind. Mrs. Renshaw wanted more different kinds of vegetables, so she suggested having only four of each kind. Mr. Renshaw didn't like that because if some of the plants died, there wouldn't be very many left of each kind. So they agreed to have five of each vegetable. But then their daughter pointed out that there was room in the garden for two more plants, although then there wouldn't be the same number of each kind of vegetable. To remedy this, she suggested buying six of each vegetable. Everyone was satisfied with this plan. Given this information, what is the fewest number of vegetable plants the Renshaws could have in their garden? (Novick, 1988, p. 513)

The subjects were given a method for solving the analogous problem, but not a method for solving the target problem. The novices were not affected by seeing the analogous problem, but the experts demonstrated positive transfer from the analogous problem to the target problem.

In another situation, the first author observed a biochemistry class in which an instructor shared an analogy comparing the process of putting a hand in a rubber glove to the induced fit model of enzyme/substrate binding. The author thought the analogy was a wonderful way to visualize the flexibility of enzymes and their ability to adapt their shapes to those of their substrates (just as the shape of the glove adapted to the shape of the hand). She discovered, however, that the analogy was not as useful to the students as it was to her. The students understood that the point of the analogy was to convey the complementarity of the shapes of enzymes and substrates. The students, with their limited understanding of biochemistry, were not able to recognize the purpose of the analogy or use the analogy to the degree intended by their instructor.

Conflicting results were seen in a study by Donnelly and McDaniel (1993), in which students who were learning a previously unfamiliar scientific concept ("novices" in the terms of the Novick study) were divided into two groups. One group was taught with analogies; the other was not. The novice students who were taught with analogies outperformed their peers who were not.

The apparent inconsistency between the results obtained by Novick and by Donnelly and McDaniel can be explained by arguing that experts may be able to recognize and use analogies more easily than novices, but novices may benefit more from the use of analogies than experts. The challenge for teachers is to determine how to help novices recognize and use analogies for their benefit. After all, even students with high-level reasoning abilities can be novices in a field in which information is new to them.

Potential Beneficial Roles of Analogy

Analogies are most often used in an educational setting to help students understand new information in terms of already familiar information and to help them relate that new information to their already existing knowledge structure (Beall, 1999; Glynn, 1991; Simons, 1984; Thiele and Treagust, 1991; Venville and Treagust, 1997). It has been argued that "knowledge is constructed in the mind of the learner" (Bodner, 1986, p. 873). As they construct knowledge, learners seek to give meaning to the information they are learning, and the comparative nature of analogies promotes such meaningful learning. Ausubel, Novak, and Hanesian (1978) state that in order to learn meaningfully, individuals must choose to relate new knowledge to concepts they already know.

By their very nature, analogies relate information in a familiar, analog domain to information in an unfamiliar, target domain. Lemke notes:

> What makes an analogy work is very simple in thematic terms. An analogy sets up a simple correspondence between two thematic patterns. The patterns have different thematic items, but the same semantic relations between them. One pattern is already familiar, the other new. Students learn to transfer semantic relationships from the familiar thematic items and their pattern to the unfamiliar items and their pattern. (Lemke, 1990, p. 117)

There are several roles that analogies can play in promoting meaningful learning. First, they help learners organize information or view information from a new perspective. Thiele and Treagust (1991) argue that analogies help to arrange existing memory and prepare it for new information. Consider an analogy that has been used to help high school chemistry students understand the general organization of the periodic table. The analogy compares the periodic table to the geography of the United States. The United States is divided into different regions—the West, the Midwest, and the East—on the basis of similarities in the geography and weather patterns of the states in each region. Similarly, elements are grouped in the periodic table—as metals, metalloids, and non-metals—based on similarities in their physical and chemical characteristics. Certainly, the analogy could be extended to explain the organization of the periodic table in more detail; but, in the case of beginning high school students, the analogy provides a way for students to mentally organize the information they will learn about the periodic table.

Analogies can also give structure to information being learned by drawing attention to significant features of the target domain (Simons, 1984) or to particular differences between the analog and target domains (Gentner and Markman, 1997). Gick and Holyoak (1983) argue that analogies can "[…] make the novel seem familiar by relating it to prior knowledge [and] make the familiar seem strange by viewing it from a new perspective" (p. 2).

For example, Stephanie, a biochemistry student, had heard in previous classes that DNA is like a blueprint. She had a partial understanding of the analogy, that DNA contains the information needed to create an organism. However, she had never considered the other implications of the analogy, namely that a blueprint is a two-dimensional overhead view of an object to be made. DNA, on the other hand, is not a two-dimensional picture of what is going to be made. Her instructor explained that, in his opinion, DNA is more like a recipe than a blueprint because DNA contains the information needed for making something instead of a picture of something to be made. His explanation caused Stephanie to think about DNA in a different way than she had previously, even though she had a hard time putting her new understanding into words. If nothing else, the new analogy caused Stephanie to look more deeply at her own understanding of the concept:

> Stephanie: I've always been taught in class…they always say blueprint, so [Dr. Carter's analogy] actually opened my eyes that it's really not like a blueprint because I always think…I don't know…my definition of blueprint, I kind of think, "OK…here's what has to be made and, like, the cell's going to use," like a blue…it's kind of like a blueprint. I know it's not exactly like a blueprint, but you can see…if you think of the word "blueprint," you're like, "OK. Here's what has to be made and then the cell reads it and then it makes it." So, it's like…I guess I kind of think of a blueprint of how much detail a blueprint actually goes into and, then, yeah, it would be more like a recipe if you actually thought about how in depth a blueprint really is. I was like, "a blueprint is the copy and then you figure out what it is from that." So, at least it changed my thinking that it's not really like a blueprint.

Analogies may also help students visualize abstract concepts, orders of magnitude, or unobservable phenomena (Dagher 1995a; Harrison and Treagust, 1993; Simons, 1984; Thiele and Treagust, 1994; Venville and Treagust, 1997). When they do this, they can provide a concrete reference that students can use when thinking about challenging, abstract information (Brown, 1993; Simons, 1984). One of the difficult concepts for a beginning chemistry student to understand is the relative size of an atom and its nucleus. A teacher's saying that the atom is about 100,000 times larger than the nucleus may not have any physical reality for a student. However, comparing the relative size of a nucleus and an atom to the relative size of a marble in a football stadium may give the student a way to visualize the concept.

Analogies can play a motivational role in meaningful learning (Bean, Searles, and Cowen, 1990; Dagher 1995a; Glynn and Takahashi, 1998; Thiele and Treagust, 1994). The use of analogies can result in better student engagement and interaction with a topic. Lemke (1990) asserts that students are three to four times more likely to pay attention to the familiar language of an analogy than to unfamiliar scientific language. The familiar language of an analogy can also give students who are unfamiliar or uncomfortable with scientific terms a way to express their understanding of and interact with a target concept. Dagher (1995a) argues that the language of analogies can demystify scientific language and notes that the use of narrative analogies tends to result in higher student motivation and engagement.

Motivation is not only a product of the students' interest in a topic, but also of their beliefs about their abilities to successfully understand or solve a problem in that topic area; and analogies can affect both of these contributors to motivation. Analogies can make new material interesting to students, particularly when the analogy relates new information to the students' real-world experiences (Thiele and Treagust, 1994). They can also increase students' beliefs about their problem-solving abilities. Although students may initially believe themselves incapable of solving a new problem or of understanding new information, their beliefs about their abilities may change when the new problem or new information is related by analogy to a problem or information they have already been successful in solving or understanding (Pintrich, Marx, and Boyle, 1993).

Students we have interviewed mention that when instructors use analogies in class, they are indicating their concern for their students and their learning. Likewise, the instructors we have interviewed believe that good instructors make information understandable through analogies. The students' perception of their instructors' concern for them seems to motivate them to study and learn.

Finally, as mentioned earlier in this chapter, analogies can play a role in promoting conceptual change by helping students overcome existing misconceptions (Brown, 1992, 1993; Brown and Clement, 1989; Clement, 1993; Dagher, 1994; Dupin and Johsua, 1989; Gentner et al., 1997; Mason, 1994; Venville and Treagust, 1996). Ideally, analogies can help students recognize errors in conceptions they currently hold, reject those conceptions, and adopt new conceptions that are in line with those accepted by the scientific community. Analogies may make new ideas intelligible and initially plausible by relating them to already familiar information. If students can assimilate new information in terms of their existing knowledge, they are likely to be able to understand that information, relate it in their own words, and comprehend how that new information might be consistent with reality—all necessary conditions for conceptual change (Posner, Strike, Hewson, and Gertzog, 1982). Conceptual change is discussed in Chapter 7 of this book.

Multiple analogies can also play roles in conceptual change. Brown and Clement (1989) have developed the "Bridging Analogies Strategy" to help students overcome misconceptions. In this strategy, instructors first try to make a misconception explicit by asking a target question. They then present a case that they see as analogous and try to establish the similarity/analogy relation. If students do not see how the analogous situation applies to the target situation and do not transfer knowledge from the analogous situation to the target situation, instructors introduce another analogy, one that is conceptually midway between the first analogy and the target concept. This process continues incrementally until the students can see the similarity between the first analogy and the target concept and transfer knowledge from the first analogous situation to the target situation.

In one specific example, Brown and Clement (1989) were trying to help students understand the upward force that a table exerts on a book (which most students could not fathom). They did this by going through a series of analogies ("bridging analogies"), each of which more closely approached the target concept than the previous. They started by asking students if there was an upward force when books rest on an outstretched hand. Although the interviewed student agreed that his hands did exert an upward force on the books, he could not see how this situation was analogous to that of a book sitting on a table. The interviewer introduced another analogy—that of a book resting on a spring. This time, the student did not understand that the spring exerted an upward force, so the interviewer introduced another bridging analogy—that of a hand pushing down on a spring. The student did believe that the spring would exert an upward force on his hand because he saw his hand as actively pushing on the spring while the book resting on the spring was passive.

As an attempt to help the student understand that a spring does, indeed, exert an upward force on a resting book, the interviewer introduced yet another bridging analogy—that of a hand resting on the book which was resting on a spring. This analogy helped the student see that an upward force is exerted by a spring on any object resting on it. However, the goal was to help the student see that a table exerts an upward force on a book. To this end, the interviewer introduced two ideas: a pile of books resting on a flexible board and a hand resting on a flexible board. Although, initially, the student did not think that the flexible table exerted an upward force, he reasoned that the flexible table was similar to the spring and would exert an upward force. Ultimately, he could make the connection between the flexible table exerting an upward force on a book and a table exerting a force on a book.

The series of bringing analogies helped the student to incrementally change his views towards the views of physicists. While this approach was effective for the student, there is also evidence that "experts" use bridging analogies when problem solving to increase their confidence in a problem solution or the problem-solving process (Clement, 1993).

Ideally, if students view the analog and target as analogous and they understand the analog concept, they will change their conception of the target concept. However, this is not always the case. In one case cited by Brown and Clement (1989), those conditions were met, but the student did not change his ideas about the target concept. Although he found the analogous situation intelligible, he did not find it plausible (reflecting the real world), so he did not transfer analog concepts to the target concept. In cases where conceptual change resulted from the use of bridging analogies, the authors note that the analogies helped enrich students' conceptions of the target concepts, and they suggest that this enrichment was necessary to affect conceptual restructuring.

Potential Negative Results of Analogy Use

As with any other teaching technique, the use of analogies in a classroom can have a negative effect. Some of these negative effects can be avoided if teachers follow certain guidelines when teaching with analogies (see Glynn, 1991; Treagust, 1993; Zeitoun, 1984), but at least some of these negative effects are possible even when teachers follow those guidelines. Although both teacher and student may consider an analogy useful for learning new information, the analogy might be superfluous information if the student already has an understanding of the target concept being taught (Venville and Treagust, 1997). In one biochemistry class, an instructor compared hydrogen bonds to Velcro. Individually, hydrogen bonds are weak, but large numbers of hydrogen bonds can act together to stabilize and strengthen a structure. Similarly, although one hook and eye of Velcro is not strong, thousands of Velcro hooks and eyes working together have the strength to hold two materials together. While this analogy might have been useful to someone who is beginning to learn about hydrogen bonds, it was not useful for the students in the biochemistry class who already had a good understanding of the concept of hydrogen bonds.

Students may resort to using the analogy mechanically, without considering the information the analogy was meant to convey (Arber, 1964; Gentner and Gentner, 1983; Venville and Treagust, 1997). For example, a student may answer an exam question with an analogy (Question: “What is the function of the mitochondrion?” Answer: “The mitochondrion is the power plant of the cell.”). Part of the mechanical use of analogy may be due to the students’ not being willing to invest time to *learn* a concept if they can simply remember a familiar analogy for that concept, since familiar analogies can often provide students with correct answers to exam questions—even if those analogies are not understood (Treagust, Harrison, and Venville, 1996).

A chemistry instructor noted that each year students had difficulty predicting the relative pH of ionic salts when they dissolve in water. One year, he decided to begin a lesson on the hydrolysis of salts by asking students to think of the relationship between dominant and recessive genes in parents in relationship to children. He asked if one parent had brown eyes and the other blue eyes, what eye color would their child most likely have? He next told students that the parents of the salt (an acid and a base) could be classified as being either strong or weak. The child of the parents, the salt, would have pH characteristics of the dominant parent. For example, sodium acetate can be made by reacting sodium hydroxide, a strong base, with acetic acid, a weak acid. When placed in water, the salt solution should be basic because it has a strong base for one of its parents. The students immediately understood this analogy and the class was very successful at predicting the relative pH of salt solutions. The instructor admonished the students that they could not use this analogy when explaining why the solution was acidic, basic, or neutral. However, when asked to explain why certain solutions were acidic, basic, or neutral on an examination, the majority of students cited the strong versus weak parent as a reason.

The mechanical use of an analogy may also be due to students’ inability to differentiate the analogy from reality. An analogy never completely describes a target concept. Each analogy has limitations. Unfortunately, students usually do not know enough about the target concept to understand those limitations. For this reason, they may either accept the analogical explanation as a statement of reality about the target concept or incorrectly apply the analogy by taking the analogy too far. Beall, using the word “metaphor” to mean either “metaphor” or “analogy,” says that this is often the case in biochemistry and gives a particular example:

> Concepts in biochemistry are very commonly understood using language as a metaphor. For example, a letter is the metaphor for a single amino acid residue in

> a protein; a word corresponds to the secondary protein structure; and so on, up to a complete book, which corresponds to the entire cell. This metaphor is so attractive that it colors thinking about these subjects and if carried too far can lead to erroneous impressions. (Beall, 1999, p. 367)

When students inappropriately apply irrelevant concepts from the analog domain to the target domain, they can develop misconceptions about the target domain (Brown and Clement, 1989; Clement, 1993; Duit, 1991; Glynn, 1995; Kaufman, Patel, and Magder, 1996; Thagard, 1992; Zook, 1991; Zook and DiVesta, 1991; Zook and Maier, 1994). An analogy that is often used in biochemistry compares a cell to a factory and the different organelles to parts of the factory. Students who know a lot about factories but little about the cell might assume that the cell, like the factory, has a limited number of entrances. These misconceptions that are developed as the result of an analogy can be difficult to remedy.

Finally, although one of the purposes of an analogy is to help students learn a concept meaningfully by relating that concept to the students' prior knowledge, the use of an analogy may limit a student's ability to develop a deep understanding of that concept (Brown, 1989; Dagher, 1995b; Spiro, Feltovich, Coulson, and Anderson, 1989). When only one analogy is used to convey information about a particular topic, students may accept their teacher's analogical explanation as the only possible or necessary explanation for a given topic.

Spiro, Feltovich, Coulson, and Anderson (1989) found that medical students were kept from a full understanding of concepts associated with myocardial failure because of analogies they had learned. They noted:

> […], although simple analogies rarely if ever form the basis for a full understanding of a newly encountered concept, there is nevertheless a powerful tendency for learners to continue to limit their understanding to just those aspects of the new concept covered by its mapping from the old one. Analogies seduce learners into reducing complex concepts to a simpler and more familiar analogical core. (Spiro, Feltovich, Coulson, and Anderson, 1989, p. 498)

It may simply be more convenient for students to think of a concept as being explained by one familiar analogy than to invest the time to learn a new explanation for or develop a correct understanding of that concept.

Teaching Models

Although analogies can form conceptual bridges between knowledge that students have and new information, their incorrect use can lead the students to develop incorrect ideas about target concepts. Observational studies have shown that teachers often use analogies spontaneously and, usually, unsystematically (Glynn, Duit, and Thiele, 1995; Thiele and Treagust, 1994). Several authors have suggested that teachers could use analogies more effectively if they had guidelines for teaching with analogies. Three major teaching models are presented in the analogy literature: the Teaching-With-Analogies (TWA) model, the General Model of Analogy Teaching (GMAT), and the FAR (Focus, Action, Reflection) model.

Teaching-With-Analogies Model (TWA). The teaching model cited most frequently in the literature is the Teaching-With-Analogies model (Glynn, 1991, 1995, 1996). Glynn developed his guidelines for teaching with analogies by examining what he considered to be exceptional analogies from science textbooks. The Teaching-With-Analogies model outlines six steps that teachers should follow when using analogies as teaching tools. Each step is consistent with factors that have been reported as having positive effects on correct analogical transfer:

- Introduce the target concept,
- Present the analog concept (a concept with which the students should be familiar from previous experience),
- Identify the relevant features of the target and analog concepts,
- Explicitly map the similarities between the target and analog concepts,
- Indicate where the analogy breaks down, and
- Draw conclusions about the target concept based on the analog concept.

While these steps do not need to be followed in any certain order, teachers should include the features of each of the six steps outlined above in any discussions that include analogies.

Although the TWA model is mentioned extensively in the analogy literature, relatively few studies have examined its effectiveness. Treagust, Harrison, and Venville (1996) tutored seven high school teachers in the TWA model of analogy instruction and then observed sessions in which the teachers used analogies and comparable teaching sessions in which the same concepts were taught without the use of analogies. After the teaching sessions, they interviewed students and teachers about the concepts that were taught and examined interview transcripts for evidence of conceptual change. In particular, they looked for statements that would indicate that the students found their explanations for certain phenomena as intelligible, plausible, or fruitful (Posner, Strike, Hewson, and Gertzog, 1982; Strike and Posner, 1985).

Treagust, Harrison, and Venville (1996) determined that students who were taught with an analogy by the TWA model demonstrated a higher-level conception status than students who were not taught with the analogy. In each of the three case studies described, the authors felt that the use of the analogy was an essential link to the students' ability to make sense out of phenomena. Only one of the students in the case studies used the analogy spontaneously, but the other two students made "conceptual progress" when reminded about the analogy. It appears that analogies can, indeed, promote meaningful learning and conceptual growth when used systematically and in accordance with the TWA model.

General Model of Analogy Teaching (GMAT). Zeitoun's General Model of Analogy Teaching (GMAT) differs from the TWA model in that it describes additional pedagogical aspects of teaching with analogies (Zeitoun, 1984). Zeitoun's model emphasizes the need to plan analogies before using them, to take into account students' prior knowledge and abilities, to evaluate the effects of the analogy, and to revise the analogy to meet the needs of the students. The GMAT model consists of the following steps:

- Measure some of the students' characteristics related to analogical learning in general;
- Assess the prior knowledge of the students about the topic;
- Analyze the learning material of the topic;
- Judge the appropriateness of the analogy to be used;
- Determine the characteristics of the analogy to be used;
- Select the strategy of teaching and the medium of presenting the analogy;
- Present the analogy to the students (including its purpose, the analogous attributes, the transfer statements, and the irrelevant attributes);
- Evaluate the outcomes of using the analogy in teaching (determine whether students use the analogy to study the topic, assess the students' knowledge of the attributes of the topic, and identify the misconceptions that result from the analogy); and
- Revise the stages of the model if needed.

Zeitoun claims that analogies will be used more effectively and with less misconceptions if teachers follow his guidelines, but we have not seen any reports of studies of the effectiveness of this model.

FAR (Focus, Action, Reflection) Model. Treagust and his colleagues (Treagust, 1993; Treagust, Harrison, and Venville, 1998) developed their FAR (Focus, Action, Reflection) model after observing five experienced teachers who used the TWA model with their favorite analogies. They found that although these experienced teachers did use each of the steps of the TWA model of teaching with analogies when they taught, they did not use the steps in any consistent order. Instead, they modified the order of the steps to meet the needs of their students and of the lesson they were teaching. These teachers also spent some time preparing their analogies before instruction and reflecting on the effects of using the analogy after instruction—actions that Treagust, Harrison, and Venville felt were necessary for the teachers' effective use of analogies. Accordingly, the FAR guide integrates preparation and reflection stages into the actual instruction stage of using analogies.

The FAR guide is simpler than either the TWA or GMAT models and is so by design. The developers of the FAR guide felt that there were too many steps to remember in the TWA and GMAT models, so they wanted to develop a guide for teaching with analogies that any teacher could remember easily (Treagust, 1993; Treagust, Harrison, and Venville, 1998). The steps of their FAR guide are found below (Treagust, 1993, p. 299):

> FOCUS on the concept being taught and the analog to be used. Is it difficult, unfamiliar, or abstract? What do students know about the concept? Are students familiar with the analog?

ACTION. Explicitly connect the similarities between the analog and target concepts and discuss the limitations of the analogy.

REFLECTION. Evaluate how the analogy came across to the students and make improvements as needed.

The effects of using the FAR guide have not been investigated; however, there is one example in which the FAR guide was successfully used to teach a topic with analogies. Harrison and Treagust (2000) observed 11^{th}-grade chemistry students who were taught about atoms and molecules by their regular classroom teachers who used analogies in a systematic way, with reference to the FAR guide. All formal and informal discussions about the topics were taped, and the investigators collected student work and interviewed students in order to determine their conceptions. The authors present a case study of one of the students, who they call "Alex, the multiple modeler." The way that Alex used the multiple analogies/models of atomic structure throughout the class provided evidence that he had changed his initial conceptions about atomic structure in favor of more scientific conceptions. Initially, Alex believed that an atom was composed of a large nucleus with closely-situated, orbiting electrons. However, after instruction with analogical models, Alex used multiple models to describe his new conception of an atom as consisting of a central nucleus surrounded by spacious (more spacious than his original description), swirling electron clouds.

Summary

There are several potential advantages to using analogies in a chemistry classroom. Analogies can help students visualize abstract concepts, organize their thinking about a given topic, and learn a topic meaningfully. They can also motivate students to learn. There is always, however, a danger that analogies will be misinterpreted or misunderstood by students. Teachers often use analogies unsystematically in their classroom teaching, and that unsystematic use may result in the development of misconceptions about target concepts or, at the least, less effective analogical transfer than is possible. Several authors have suggested models by which analogies can be taught effectively. Following these models and understanding the advantages and disadvantages of analogy use may help instructors to use them more effectively in the chemistry classroom.

Effectively used analogies can help students understand difficult concepts, often with surprising results. Earlier this year, we explained the concepts of compounds, elements, and mixtures to our high school students. We defined the different systems and drew pictures on the chalkboard representing microscopic views of these systems; however, the students did not seem to understand the differences between them. In an attempt to explain the systems, we told the students about a cereal analogy for compounds, elements, and mixtures.

In this analogy, mixtures are compared to Raisin Bran cereal because it contains two separate components (the raisins and the flakes), and the composition of a sample of Raisin Bran differs depending on where you take the sample: if you take the sample at the bottom of the box, you will get more raisins than if you take a sample from the top of the box. Compounds are compared to Crispix cereal because each time you reach into a Crispix box, you will pull out the same pieces: a “bonded” square made of rice on one side and corn on the other.

Having described the analogies for compounds and mixtures, we asked the students to identify cereals that would be analogies for elements. The students’ response was incredible. Students who do not normally participate in class discussion were volunteering cereals that could be called analogical “elements”: cheerios, fruit loops (if you ignore the colors), and corn flakes. One student, who struggles in chemistry class, raised his hand and used an analogy to check his understanding of the definition of “compound.” He asked, “Well, would Frosted Mini-Wheats be a compound?” When we asked him to explain what he meant, he said, “When you reach into the box, you always get the same things, but each thing in the box is made up of two parts: a frosted side and an unfrosted side.” For this particular student, this conclusion was brilliant. Although he did not understand the initial description of compounds, the analogy helped him make sense of what, for him, was a difficult concept. You can see similar results from using analogies in your chemistry class when you plan your analogies and carefully explain them in class. The students like analogies, and they do use well-explained analogies to learn!

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