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Methods and issues of teaching and learning

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WHAT RESEARCH TELLS US ABOUT USING ANALOGIES TO TEACH CHEMISTRY

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ABSTRACT. Analogies can be powerful teaching tools because they can make new material intelligible to students by comparing it to material that is already familiar. It is clear, though, that not all analogies are good and that not all "good" analogies are useful to all students. In order to determine which analogies are useful for students and how analogies should be presented to be useful for students, we interviewed biochemistry students about the analogies that were used in their classes. We found that most biochemistry students like, pay particular attention to, and remember the analogies their instructors provide. They use these analogies to understand, visualize, and recall information from class. They argue, however, that analogies are not presented as effectively as they could be in class. We present their suggestions for improving classroom analogy use. [*Chem. Educ. Res. Pract.*: 2004, *5*, 15-32]

KEY WORDS: analogies; analog domain; biochemistry; phenomenography; qualitative research; target domain

INTRODUCTION

Chemistry and biochemistry classes are full of abstract concepts that are not easy to understand unless they are related to something from our everyday experiences. Effective analogies can clarify thinking, help students overcome misconceptions, and give students ways to visualize abstract concepts. Misleading or confusing analogies, on the other hand, can be more than just a waste of class time; they can interfere with students' learning of class material.

In the simplest sense, an analogy is a comparison between two domains of knowledge — one that is familiar and one that is not. The familiar domain is often referred to as the "analog" domain; the domain that needs to be learned is usually referred to as the "target" domain. 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 & 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).

Potential positive results of analogy use

Analogies are most often used 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 & Treagust, 1991; Venville & 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. "To learn meaningfully, individuals must choose to relate new knowledge to relevant concepts and propositions they already know" (Ausubel quoted in Bodner, 1986, p. 877).

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)

Analogies can play several roles in promoting meaningful learning. They can help learners organize information or view information from a new perspective. Thiele & Treagust (1991) argue that analogies help to arrange existing memory and prepare it for new information. 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 & Markman, 1997). Gick & 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).

Analogies may also help students visualize abstract concepts, orders of magnitude, or unobservable phenomena (Dagher, 1995a; Harrison & Treagust, 1993; Simons, 1984; Thiele & Treagust, 1994; Venville & Treagust, 1997). When they do this, they provide a concrete reference that students can use when thinking about challenging, abstract information (Brown, 1993; Simons, 1984).

Analogies can also play a motivational role in meaningful learning (Bean, Searles & Cowen, 1990; Dagher, 1995a; Glynn & Takahashi, 1998; Thiele & 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.

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 & Treagust, 1994). They can also increase students' beliefs about their problem-solving abilities 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, & Boyle, 1993).

Finally, as mentioned earlier, analogies can play a role in promoting conceptual change by helping students overcome existing misconceptions (Brown & Clement, 1989; Dupin & Johsua, 1989; Brown, 1992, 1993; Clement, 1993; Dagher, 1994; Mason, 1994; Venville & Treagust, 1996; Gentner et al., 1997). 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 & Gertzog, 1982).

Potential negative results of analogy use

As with any other teaching technique, the use of analogies in a classroom can have a negative effect, even when teachers follow guidelines that have been suggested for teaching with analogies (see Zeitoun, 1984; Glynn, 1991; Treagust, 1993). For example, 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 & Treagust, 1997).

Students may resort to using an analogy mechanically, without considering the information the analogy was meant to convey (Arber, 1964; Gentner & Gentner, 1983; Venville & 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 when those analogies are not understood (Treagust, Harrison, & Venville, 1996).

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 it too far.

When students inappropriately apply irrelevant concepts from the analog domain to the target domain, they can develop misconceptions about the target domain (Brown & Clement, 1989; Duit, 1991; Zook, 1991; Zook & DiVesta, 1991; Thagard, 1992; Clement, 1993; Zook & Maier, 1994; Glynn, 1995; Kaufman, Patel & Magder, 1996). The 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; Spiro, Feltovich, Coulson & Anderson, 1989; Dagher, 1995b). 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 & Anderson (1989), for example, 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 & 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.

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 (for example, see Holyoak & Koh, 1987; Brown & Clement, 1989; Donnelly & McDaniel, 1993; Harrison & Treagust, 1993; Treagust, Harrison, & Venville, 1996; Glynn & Takahashi, 1998) while other studies have reported that the use of analogies has had little or no effect on learning (for example, see Gilbert, 1989; Bean, Searles, & Cowen, 1990; Friedel, Gabel, & Samuel, 1990).

It is clear from the existing literature that not all analogies are good analogies and that not even a "good" analogy is useful for all students. In order to determine which analogies are useful for students and how analogies should be presented to be useful for students, we interviewed biochemistry students about the analogies that were used in their classes.

METHODOLOGY

We chose phenomenography as the theoretical framework to guide our research in this study because our experiences as both students and instructors of biochemical concepts have led us to believe that students have a variety of ways of experiencing and understanding both specific biochemistry analogies and analogies in general. If we understand what these conceptions are, it will be easier, as instructors, to determine what students need to learn well from analogies. Phenomenography is an empirical research tradition that was designed to answer questions about thinking and learning, especially in the context of educational research (Marton, 1986). Its aim is to define the different ways in which people experience, interpret, understand, perceive or conceptualize a phenomenon, or certain aspect of reality. This paper examines results obtained as part of a study in which the following guiding research question was used: "What are biochemistry students' perceptions of analogies and their use in biochemistry classes?"

In order to determine how students perceive the use of analogies in biochemistry classrooms, we interviewed students who were taking or had taken at least one semester of biochemistry. We asked for volunteers from two introductory biochemistry classes — a 100-level class and a 300-level class — and one upper-level chemistry class that had a biochemistry prerequisite. We also obtained volunteers from a population of advanced undergraduate and graduate students. We were able to interview 43 students: 9 students from the 100-level biochemistry class, 23 students from the 300-level biochemistry class, and 11 upperclassmen and graduate students. All oral interviews were carried out during the Spring 2002 semester.

The individual interviews were semi-structured, conversational, and lasted approximately one hour. We began by asking students about their educational background and interests. We spent the majority of the interview asking students their opinions of analogies in general: if they like analogies, what the advantages and disadvantages are of analogies, how students use analogies, and how analogies should be used to be effective in classes. The last portion of the interview consisted of our asking students about specific analogies that had been used in their classes, with the purpose of determining what the students understood about these analogies and how their understanding of biochemical concepts had been influenced by these analogies.

We transcribed each of the interviews and then continued our analysis by reading through the interviews several times to look for trends in the student opinions about the use of analogies in their classes, how analogies should be used in classes, how students use analogies, and how students interpret specific analogies. As we read through the interviews, we took notes about the patterns we were seeing in the transcripts.

Because of the volume of interview data collected, we used the data management program Atlas.ti (Scientific Software) to code the data and to divide it into manageable portions. We used the notes compiled about trends in student responses as an initial coding scheme. As we read through the transcripts once again to code them in Atlas.ti, we developed new codes and deleted others. We also developed descriptions of the codes. Once we had developed descriptions of the codes, we reread and recoded the transcripts until the coding decisions we made were consistent with the coding descriptions we developed. All students were given pseudonyms by which they will be known in this study, as were the faculty who taught the classes from which interview data were collected.

RESULTS AND DISCUSSION

Not surprisingly, most students said that they liked it when teachers used analogies in class. This was true of students at all levels, from freshmen to graduate students, though students had different reasons for liking analogies and finding them useful. For example, Alyson, a junior pre-vet major, said the following about the analogies being used in her biochemistry class:

> Alyson: I like the analogies. They do break up the class. You know? And for people who don't … can't just look at a paper and, like, read it and get what he's talking about, it helps … And it's funny. I don't know. It's fun.

She continued to say that she enjoyed analogies not only because they are entertaining in class but also because they help her learn. When asked why she liked analogies, Alyson responded:

> Alyson: I generally remember the analogies more than, like, the scientific definition, but, then, if I can remember those analogies, I'm better off. Like, I have more of a chance of remembering them and bringing them back on a test than I do if they don't give anything but the scientific definition. You know?

Another junior student, Susan, also said that analogies help her remember classroom information more easily than she would be able to without the analogies. She indicated that analogies helped her understand which class information was most important to the instructor.

> Susan: I think it breaks up the material a little bit, and it … it's usually something that you can visualize or something you can think about and then you think, "oh, that's that." And it's really hard to think of them off my head. I would have brought a list of them, but when you're on your test, you see something, and you say, "I remember that," and that really helps, I think. It helps to put it in your memory bank. If they stop and make a big deal about it or stop and … then you know it's important and you know you need to remember it. And you know if it's

> off the subject usually, it's not something that's just part of the gist. … they usually stop for a second, and I think that can help you remember it better, and understand it better.

Tricia, a freshman biochemistry major, said that she liked the analogies that were used in her class even though she does not remember using those analogies to learn outside of class. The analogies helped her understand material as it was presented in class and to easily recall information that was taught in the class later.

> Tricia: I think that what it is is you don't think about it, but the minute somebody asks you about it or the minute something's brought up that you have seen an analogy for, it comes back. You know, you don't think about it. You don't think, "oh … well, I remember so and so used all these analogies." It's more like when somebody says, "do you remember this." You go, "yeah … I remember 'cause he brought this in and it worked out. … it helped me understand it." So, I think it is a useful tool, and even if you don't think about it, whenever it comes down to remembering something, you will remember it better using an analogy. You remember it because you remember, "oh, yeah … well, that's … that was the time when so and so brought in a squash," you know, and that type of thing, so I think it is useful. I think it sparks something in your memory, and you remember it because it's different, 'cause it's not just somebody up there talking.

What do students say about useful analogies?

Students know that analogies can help them learn and remember concepts in their biochemistry classes, but they also know that not all analogies are "good." They believe that many of the reasons that analogies are not useful are related to the ways in which their instructors present analogies in class. Because students know that analogies are potentially useful and because they do not believe that their instructors plan the analogies used in class, they have several suggestions for improving classroom analogy use. They have suggestions about when analogies should be used, what kinds of analogies are good or useful, and how analogies should be presented in class to be useful.

When should analogies be used?

When target concepts are difficult or challenging

The students argued that analogies are very useful when an instructor is trying to explain difficult or challenging information, especially when students look confused in class.

> Alyson: ... I think analogies are most important when it's a really hard concept because if it's easy, you don't really need analogies. Most people would understand it off the top, but, I mean, if it's something that you think that your students in the past had a hard time with or whatever, I think it's really important to give an analogy if you can without confusing people even more, which is important 'cause some people don't give good analogies, but some people give really good analogies.

Of course, an analogy that is useful for explaining a topic that is difficult for students in a 100-level class is not necessarily useful for students in upper-level or graduate-level classes, where students expect to learn target concepts in greater detail. For example, in the 100-level biochemistry class for biochemistry majors, Dr. Williams provided an analogy to help his students understand the binding of oxygen to the different subunits of hemoglobin. He pulled out a 2 x 2 sheet of 4 stamps and started breaking them apart. To get the first stamp out, you have to break 2 perforations; to get the 2nd and 3rd stamps out, you have to break just 1 perforation each; and to get the 4th stamp out, you don't have to do anything. Each stamp takes less energy to remove, just like it takes less energy to bind each successive oxygen to hemoglobin.

All of the students we spoke with from the 100-level biochemistry class seemed to have a good understanding of this analogy. They were able to recall the analogy as it had been presented to them in class, and they understood the main point of the analogy: that each successive oxygen binds to hemoglobin more easily than the previous oxygen just as each successive stamp is easier to tear from the pane than the previous one. The students did not make any additions to this analogy or develop any misconceptions about hemoglobin based on the analogy. In fact, they were able to easily identify the limitations of the analogy.

While the graduate students understood the analogy, they were concerned that the analogy did not give enough detail about the conformational changes associated with oxygen binding to hemoglobin. The analogy was not useful for what the graduate students wanted to learn and understand about hemoglobin. However, each of them commented that if the purpose of the analogy was to show the 100-level students the successive ease of oxygen binding, then the analogy was potentially useful for those students.

When target concepts can not be visualized

The students also thought that analogies are useful to explain or describe objects or processes that are so small that they cannot be seen with the naked eye.

> Robert: I think you should use it most ... whenever they're [the concepts the instructor is teaching] on a level that you actually cannot see what's going on. So, I think, like, the sciences are, by far, the best place to use the analogies.

When target concepts are introduced

Finally, the students said that analogies are useful to introduce new conceptual material. When asked whether there are certain situations in which analogies are more helpful than in other situations, William responded:

> William: I think analogies are more helpful when you're hitting brand new conceptual material because you're really, sometimes, wrestling with the, with the concept. You're trying to figure out how does, how does this work, and if you have something that would be a strong analogy to help put it in perspective, that would be helpful.

Sarah responded to a similar question as follows:

> Sarah: When they are first introducing a new topic because it's something you can immediately grasp and say, “OK. I'm here. I understand this” and then you can gradually understand it more.

When are analogies not useful?

When target concepts are simple or already understood

Although the students said that there could be analogies for almost any concept in biochemistry, they identified situations in which analogies were not as useful in their classes. The majority of the students we spoke with said that they could not imagine analogies for biochemical structures or pathways or for mathematical concepts. They also did not believe that analogies should be used for concepts that are "easy." Students said concepts were "easy" if either the students already understood them or if a concept could be easily explained without the use of an analogy. If instructors did use an analogy for an "easy" concept, students thought of that analogy as extra information to learn.

> Stephanie: It's like … if something is pretty straight-forward, I wouldn't use an analogy 'cause that's just, like, extra mumbo-jumbo that you really don't care about, but if something's more complex and you can tell that the class has got those scrunches on their faces and they don't really understand what's going on, then that's a good place to use an analogy ...

At the beginning of the semester in the 300-level introductory biochemistry class, Dr. Carter was talking about hydrogen bonds and mentioned that, individually, they are very weak. However, when many of these bonds act together, they are strong. He compared this to David Letterman in his Velcro suit. He asked if the students remembered seeing David Letterman in a Velcro suit. No one indicated that he had, so Dr. Carter described the suit and the human fly paper stunt: David Letterman wore a suit and jumped up against a wall made of "anti-Velcro." He, a 200-lb man, stuck to the wall. This indicates that all of that Velcro working together is strong.

He then told the students to think about one individual Velcro hook and antihook. Individually it is weak, but when you put many together, they are strong, like hydrogen bonds. He gave DNA as an example of molecules that are held together strongly by many hydrogen bonds and then referred to DNA as being like Velcro.

This was another analogy that was well-understood by many students in the 300-level class; however, it was not necessarily useful. Although all of the students we spoke with thought the analogy was entertaining and made sense, several students indicated that they already understood the concept of hydrogen bonds before hearing the analogy.

> Brent: I think it really wasn't that useful to me, but I think if I was learning, essentially, what a hydrogen bond is for the first time or if I never really completely understood it before, then it would help me.

When target concepts are overwhelming

The students also argued against the use of analogies when they felt overwhelmed by the amount of information they have to learn or when they are expected to learn information in too short a period of time. Amanda, for example, was interviewed two days before she was scheduled to take an exam that covered glycolysis, the citric acid cycle, oxidative phosphorylation, and photosynthesis in her 300-level class. As we talked, Amanda expressed her anxiety about the upcoming exam.

> Amanda: I think that if you're going to, you know, with the pathways and everything … if you're going to bog us down with glycolysis, I'm not going to focus so much on your analogy

> because there's not enough time to say, “this is the part of the analogy that associates with the redoxes, reduction [of oxidative phosphorylation].”

When target concepts must be memorized

The students also noted that analogies were not as useful when they were expected to simply memorize information for their classes regardless of whether they felt overwhelmed by the amount of information they had to memorize. When asked to comment on times when analogies are not useful, Martin responded as follows:

> Martin: Well, if someone was going to go home and memorize glycolysis and all the structures and, you know, the energy involved with it, I don't know if it would be helpful or not. The straight memorization stuff, or memorize the structure of this, I don't think it's really going to help too much.

What types of analogies are useful?: “Good” vs. “bad” analogies

As we spoke with the students about both specific analogies and analogies in general, we found that they distinguished between “good” and “bad” analogies. The primary characteristic by which the students differentiated between these categories was the extent to which they understood the analogy — “good” analogies were those the students understood, “bad” analogies were those they did not understand. There are several features that contribute to an analogy's understandability.

Good analogies are simple

The first, and perhaps foremost, characteristic students use to distinguish between analogies that are “good” or “bad” is the simplicity of the analogies. When the analogy is either too complex or too lengthy, students stop paying attention to it or become confused by it. For example, several students commented about the length and complexity of an analogy given by the instructor of the 300-level introductory biochemistry class.

Near the end of the semester, Dr. Carter told his students that he believes that DNA is like a recipe because it contains the information needed for creating a living organism. He asked the students to imagine that they are members of a family that owns a restaurant. The family has an archival cookbook (the genomic DNA) that contains all of the recipes (genes) that are made in the restaurant. He said that, on some nights, the students may only want to make a subset of recipes (express only certain proteins). In that case, then, they could photocopy just the recipes they need (transcribe the genes that correspond to the proteins). They could even make multiple copies if they need a lot of a particular recipe and want multiple chefs working on making it (make multiple copies of a particular protein’s mRNA).

What if one particular chef wants to change a recipe? He might change the ingredients on the recipe. The students would not want the chef's changes to be passed on to future generations, so it would be better for him to work with a copy of the recipe than with the original cookbook (it is better if there are mutations in the mRNA than in the DNA). What if the cook drops the recipe in the sauce (what if the mRNA is damaged)? The students could always make another copy from the archival cookbook later on. Later, Dr. Carter said that there are upstream regions of DNA (promoters) that allow DNA polymerases to find the gene that will be transcribed. He compared these to tabs on the side of cookbook that allow someone to quickly find recipes.

The students did not see many problems with the interpretation of this analogy, but several students had problems with the analogy itself. First, the analogy was long and several additions were made to the original analogy. Students said that they did not know what target concept the analogy was trying to teach while the analogy was being presented. Therefore, they were confused while the analogy was presented. The analogy only started to make sense once Dr. Carter finished it and said that it referred to the transcription of DNA. Other students said that the analogy was so long that it was hard to remember.

> Melissa: Like today's analogy. What was it?
> I: With the recipe and the DNA?
> Melissa: Yeah. I didn't like that analogy. I mean, it was just cumbersome, I thought. Too much.
> I: So, what [is] a bad analogy?
> Melissa: It's long. It's … like today's [analogy]. It's a really long analogy. He even took a breath afterwards because he knew, too. It makes you think too much. If you have to think too much about it, I don't think it's a good analogy.

Good analogies are easy to remember

The students also noted that analogies are "good" when they are easy to remember. Martin, a graduate student in animal sciences, commented about a specific analogy that he liked. When asked what made it a decent analogy, he responded: "It's something that's kind of stupid and simple and easy to remember."

Beth, a student from foods and nutrition, noted that she liked analogies that teachers brought up and then built on time and time again. When asked why analogies were more useful when you can build on them, she responded:

> Beth: ... it's more useful if you could build on it because then your … if it's a good analogy, you're stepping it up. You keep on using that analogy. If it works for a student, then you keep on using it. You keep on … you remember it better, and it gives you something to grasp once a concept starts getting more difficult. Once the information starts to build, you've still got that basic idea down, and that's something that you can fall back on if you're confused …

Good analogies have familiar analog concepts

The students also argued that good analogies use analog concepts with which the students are familiar. Consider the following responses to a question that asked what characteristics make an analogy good or useful.

> Pam: I guess just similarity. If I … if you're comparing the topic to something that I'm familiar with and that I feel comfortable with, then I think that it's probably going to work for me.
> Sherry: If your analogy can be simplified to something that everybody's been exposed to, then that makes it good.

Theoretically, an analogy functions because students are familiar with the analog concept and can transfer information about the analog concept to the target concept, but students mentioned that analogies *should* do this so often that we concluded that instructors often use analog concepts that are not familiar to students.

After he spoke about glycolysis and the citric acid cycle, Dr. Carter spoke about the way the energy from metabolism of glucose is harnessed in the synthesis of ATP. He talked about mitochondrial electron transport and how it converts energy from one form (NADH, $FADH_2$) to another (ATP). He said that this process was like a Rube Goldberg apparatus in which energy is not created or destroyed but converted from one form to another.

This analogy was not successful in conveying information about the interconversion of energy that occurs during mitochondrial electron transport. The main problem with this analogy seems to be that many of the students in the 300-level class are not familiar with Rube Goldberg apparatuses.

> Tonya: Every time he used that word [a Rube Goldberg apparatus], I did not know what he way saying. I've never even heard that before, so I'm like, “what in the heck is that Goldberg machine?” and he never did tell us what that was, so I just kind of had to leave that one go 'cause I didn't know what he was talking about.

Even the few students who said that they knew what a Rube Goldberg machine was interpreted the analogy in a different way than what Dr. Carter indicated in class. For example, some of these students believed that electron transport was like a Rube Goldberg apparatus simply because both consist of multiple steps.

> Brent: Yeah. I don't know a whole lot about Rube Goldberg machines, except they've got a lot of steps, supposedly. That's all I know. I've never seen one. When I was in high school, I guess someone made one. I never saw it. It was just a lot of different steps. That's how I saw Rube Goldberg, and so that's how I applied it to the electron transport chain. So, it was just a lot of different steps. He could have just said, “it's a lot of steps,” and that would have been the same for me.

Whether an analogy is “bad” or not depends on more than whether the analog concept is familiar to the students. In some cases, students are so familiar with the analog concept that they know there are many characteristics of the analog concept that cannot be transferred to the target concept. The differences between the analog and target concept are so apparent to the students that they cannot use the similarities between the two concepts to learn from the analogy. In other cases, students understand the analog concept, but they do not believe that either the analog concept functions the way that the instructor explains or that the target concept functions as the analog concept does. For example, Dr. Carter compared the way small molecules fit through the holes in gel filtration beads to the way rice can fit in the holes that are left when cooked spaghetti congeals in a strainer. One of his students, Julie, could not imagine rice falling through congealed spaghetti. She noted that this was not a good analogy and then commented:

> Julie: I don't remember exactly, but he just talked about spaghetti and, like, the rice falling through it and … I don't know … I'm a food science major, so I'm just thinking, “I don't think it's that easy for rice to fall through spaghetti all tangled up like that.”

How should analogies be presented in class?

Overall, students said that analogies are most useful to them when they understand both the analog concept to which a target concept is being compared and the relationships that exist between the analog and target concepts. They had various suggestions for their professors to make analogy use more effective in classrooms.

Make the purpose for using the analogy clear

One of the things that students consistently mentioned was that professors should tell their students what they expect the students to understand or remember about the analogies they use. Otherwise, students may remember parts of the analogy that are not useful. However, if instructors make their purposes for using an analogy clear, it is possible that the students will remember the point of the analogy, the take-home message, even if they do not remember the analogy itself. This is particularly important when instructors use one analogy to replace or build upon another, more familiar analogy because students are very unwilling to give up analogies that are well-known to them or which have been useful to them in the past. In one of the classes involved in this study, the instructor used a hand and glove analogy as an alternative to the classic lock and key model of enzyme-substrate complementarity.

In his 100-level class he noted that the glove has the general shape of a hand, but doesn't look just like the hand (it isn't filled out, etc). However, the hand can fit into the glove, and the shape of the glove conforms to the shape of the hand. The instructor suggested that this is similar to what occurs when the substrate binds to the enzyme. The enzyme active site is roughly complementary to the shape of the substrate, but the enzyme undergoes conformational changes induced by substrate binding to become complementary to the substrate.

All except for one of the students we spoke with remembered this analogy and thought that it was useful. However, what they understood about the analogy varied greatly from student to student. Most of the students we spoke with said that the analogy taught them that the shapes of enzymes and substrates are complementary, the same concept that is usually taught with the lock and key analogy. When asked to comment on what the instructor was trying to get across to the class with the hand and glove analogy, Ashley commented:

> Ashley: That, like, you can't put your glove on your foot. It wouldn't fit. I mean, you realize that the enzyme fits the substrate.

The intention of the analogy was to have students understand the induced-fit model of enzyme-substrate complementarity, but none of the 100-level biochemistry students and just under half of the 300-level biochemistry students understood that message of the analogy. Two students said that they learned that enzymes are flexible from the analogy, but their conclusion about the flexibility of enzymes was that enzymes could catalyze reactions for a variety of substrates. If enzymes are flexible could they not conform to different substrates? Many students simply said that the point of the analogy was to indicate strict structural complementarity between enzymes and their substrates; they also indicated that they felt the lock and key analogy was sufficient to convey that point.

Because there were many students who only understood enzyme-substrate complementarity from the analogy, we reminded students during their interviews that their instructors had used both the lock and key analogy and the hand in glove analogy and asked why the instructors had focused on the hand in glove analogy. If students had not initially understood the induced-fit point of the analogy, our asking them about the two different analogies did not help them understand any more. Instead, students thought their instructors had various reasons for choosing to use the hand in glove analogy rather than the lock and key analogy. For example, they thought that the hand and glove analogy was simply easier to physically see than the lock and key analogy. When we asked Lisa why her instructor chose to share the hand and glove analogy, she gave the following response:

> Lisa: Glove's easier to find? Well, he's in a lab … or a building, probably with labs in it. Glove's easier to find than a lock and a key, maybe, possibly. Um … lock and key is an overused, almost a cliché in many, like, poems and written things. Everybody knows lock and key. Key fits in the lock. Possibly, I mean, you could just hear lock and key and you know what they're talking about. Glove in hand, you can impress that with the actual point of fitting the hand in the glove 'cause you can't actually see that the key fits in the lock, but you can't actually see that the key fits in the lock, but you can see that the hand fits in the glove. I don't know.

Finally, several students said that they were very familiar with the lock and key analogy before they entered their biochemistry classes. They could not understand why their biochemistry instructors were telling them that the analogy they had learned for so long was wrong. They did not understand that the hand in glove analogy was supposed to add to their understanding of enzymes and substrates instead of replace their understanding.

> Amanda: The only bad thing, I thought, was when he said the lock and key method is wrong. I really … you've got to realize the students have been learning that. It's been in textbooks for so long. And, I know a lot of professors will say, "your book is wrong. Don't read it." You know? But that's what, that's what we've learned, and I think it's really important to add to what we've learned and not try to take it out because that's the book.

Explain the relationships between the analog and target concepts

Students also wanted instructors to explain the relationships between the analog and the target concepts. In many cases, students could not see that there was any connection between an analog concept and a target concept. In other cases, students recognized that there must be connections between the two concepts, but they were unable to determine what those connections were or the connections to which they were supposed to pay particular attention.

> Amanda: What would I tell [my instructors]? Um … just realize that when they bring the analogy or this new piece of information in that they're trying to associate it with, that they really need to dissect the analogy and, like, take little parts of it and say, "this is why it does this … this is why it does this." … I just think you, you as a professor, have to realize that the analogy can go two different ways. It can be really confusing if you don't explain it or it can really help a student out if they understand it.
>
> Anna: The only way to use an analogy is to clearly understand … make it clear what your idea of that analogy is because it's your idea. You came up with it. There's not, like, a book of analogies out there for biochemistry that you can just go, "oh, that looks nice," you know, go plop it out there for the students. It's what your visual conception of that idea is. You understand it perfectly, but if you present it in a fashion that isn't very clear or it's an analogy that really doesn't fit, you know, like, they say, kids saying, "we don't understand what you're talking about," then you have to be able to, on the spot, think of a new one or be able to explain the one that you came up with. If you can't do that, then don't use them. Because if you can't explain them or present them in a fashion that is understandable, then there is no point in using them 'cause you're just going to throw an entire class off.

Do not overuse analogies

In addition to suggesting that their instructors explain the analogies used in class, students had other suggestions about analogy use. Many practicing chemists and biochemists we spoke with while designing this experiment expressed a fear that students would want to rely on analogies instead of learning the "real" information, and we entered the data collection phase of the experiment with the bias that, perhaps, this is what students did want. Our interviews with the students suggested, however, that this is not the case. Although students do like their teachers to use analogies in class, they did not want their teachers to overuse analogies. There were two main reasons for this: first, students may confuse concepts between one analogy and another; and, second, students do want to learn content.

> Steve: Disadvantages [of using analogies] would definitely be just using too many. Sometimes, you can put so many analogies into one little lecture that you don't remember what goes with what analogy, and that can end up making you think the exact opposite of what things really are.
> Deanne: Well, probably, I would tell [instructors] to use [analogies] carefully. Make sure you don't overuse them 'cause sometimes if you have so many analogies in class, it's like, "OK. It's a little too much for me." ... Um, 'cause you're trying to actually learn the concepts and if you have too many analogies in class, you tend to think of other stuff rather than actual concepts you're learning.

Students want to use analogies to learn, but they would rather use those analogies as a supplement to learning than as a replacement for learning the content matter.

> Beth: Use [an analogy] in a sequence. Use it as part of the explanation but not the only explanation. So, explain it in words, explain it in the words of how two biochemists or two analytical chemists or two microbiologists talking to each other would explain it. Then pictures, but then also use the analogies as a supplement rather than just what you're depending on.
> I: OK. So, if it's just a supplement, why use it at all?
> Beth: Because it's a very powerful supplement, I think. It appeals to a different part of learning … because in a class the size of the classes that I take, not everybody's going to learn the same. ... So you're appealing to different students.

Use visuals

One of the main suggestions that students from all levels had for their instructors was that they use visuals when they are presenting their analogies. Visuals add to the explanation of the analogy and appeal to more visually-based learning styles and memory, according to the students. Having a visual supplement to an analogy, whether that supplement be a two-dimensional picture or a three-dimensional physical object, seems to clear up confusion about the analog concepts that instructors are using. We asked one student what kind of advice she would give her professors who use analogies.

> Lisa: Um … oh, shoot … uh … visual aids, easy visual aids, big things, not little things, big things, easy to see, easy to use, easy to show … um … common things.
> I: OK. Anything else you'd tell him?
> Lisa: Don't say, "well, you know how this would work," "you know that that would happen," or, "if I turned the crank on this jack in the box, you know what's going to happen so let's …" NO! Do it, you know! Exciting, fun, clown pops up, it's all good, you know. People remember what you're talking about.

Visuals are not simply entertaining for the students. We asked students to recall and interpret specific analogies from their biochemistry classes. When visuals were used to supplement an analogy, students were more likely to remember the analogy and less likely to misinterpret the analogy.

Use easy-to-understand words and enthusiasm to present analogies

Students even had suggestions about how to present the analogies in class. Most students we spoke with wanted their instructors to use simple analogies and to explain them in easy-to-understand words. Melissa gave her advice to her instructor:

> Melissa: Talk about something I'm familiar with. Make it short. Use words I know.
> Not only should instructors present their analogies simply, they should present them with enthusiasm.
> Anna: You can make [analogies] in a humorous fashion, you know? 'Cause they don't have to be … science doesn't have to be serious all the time. You know? You may be talking about a deadly disease, but find a way to present the material in a humorous manner without making fun of the disease, the disease itself, but using a particular analogy.

In general, it appears that students prefer instructors who are enthusiastic in their teaching. The case is no different when it comes to using analogies in class.

Try them out first

Finally, students suggested that their instructors try the analogies out on other students before using them in class. Trying out analogies would allow instructors to determine if students will understand analogies and what problems students might encounter when trying to use the analogies their instructors provide.

> Sarah: I think analogies are good wherever you can use them, but think about them before you use them.
> I: OK. So, if you think about them, what do you need to focus on?
> Sarah: Think about what the students will know, and think about … I don't know … maybe ask a student first before you, like, go use them because I'm sure some of them were totally obvious to the professors that made them up. To other people, they're like, "ah … right … let's try and figure this one out. It's another of these crossword puzzles."

CONCLUSIONS

Most of the students we spoke with like their teachers to use analogies to explain or introduce difficult concepts in their biochemistry classes. They find that analogies are entertaining and help them understand course information. They use the analogies from class in a variety of ways, from getting an initial understanding of a concept to determining which information to pay attention to in class. There are, however, circumstances under which students do not tend to use the analogies their instructors provide in class: when they already understand the target concepts being taught, when they do not understand the analogies presented in class, when they feel they need to memorize information for an exam, and when they feel overwhelmed by the amount of information they have to learn or the amount of time in which they have to learn that information.

Overall, students believe that the specific analogies their instructors present in class are useful as long as the students are familiar with the analog concept used and as long as the relationships between the analog and target concepts are explained. The students' comments about specific analogies show that, while they believe the analogies are useful and while many analogies do convey useful information, the message of the analogies is not always obvious to them, as students can, at times, misinterpret the main points of the analogies.

Students pay particular attention to and remember analogies their instructors use in class. For this reason, it is imperative that instructors be very clear when presenting analogies.

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