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Biochemistry instructors' perceptions of analogies and their classroom use

MaryKay Orgill,^{*a} Thomas J. Bussey^b and George M. Bodner^c

Biochemistry education relies heavily on students' abilities to conceptualize abstract cellular and molecular processes, mechanisms, and components. From a constructivist standpoint, students build their understandings of these abstract processes by connecting, expanding, or revising their prior conceptions and experiences. As such, biochemistry instructors often use analogies to teach difficult or hard-to-visualize topics to their classes by relating these target concepts to more commonplace analogs with which their students may already be familiar. For example, the binding of an enzyme to its substrate is often compared to a lock and a key; and ATP is frequently referred to as a cellular energy currency in discussions of metabolism and reaction coupling. Although the use of analogies in biochemistry classrooms is fairly common, the specific ways biochemistry instructors use analogies differ from instructor to instructor and class to class. In this article, we discuss biochemistry instructors' perceptions of the use of analogies in their classroom instruction. Specifically, we discuss (1) biochemistry instructors' objectives for using analogies, (2) their perceptions of the potential disadvantages associated with analogy use, (3) the sources of the analogies they use in their classes, and (4) the ways they perceive that analogies should be presented in class to promote student learning of biochemical concepts.

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Introduction

Analogies are comparisons between two domains that are neither completely similar nor completely different. They are often used by instructors to promote transfer of a system of relationships between objects in a familiar analog domain to an unfamiliar target domain. Many studies have reported that the use of analogies resulted in beneficial outcomes (Hayes and Tierney, 1982; Simons, 1984; Beveridge and Parkins, 1987; Holyoak and Koh, 1987; Brown and Clement, 1989; Cardinale, 1993; Clement, 1993; Donnelly and McDaniel, 1993; Harrison and Treagust, 1993; Solomon, 1994; Treagust *et al.*, 1996; Glynn and Takahashi, 1998; Fast, 1999). This research suggests that there are three main roles that analogies can play in promoting meaningful learning: (1) they can help students develop an *understanding* of new information (Simons, 1984; Thiele and Treagust, 1992; Glynn and Duit, 1995; Thiele and Treagust, 1995; Gentner and Markman, 1997; Iding, 1997; Venville and Treagust, 1997; Glynn and Takahashi, 1998), (2) they can help students *visualize* new or abstract information (Curtis and Reigeluth, 1984; Simons, 1984; Brown, 1993; Harrison and

Treagust, 1993; Thiele and Treagust, 1994a; Dagher, 1995; Iding, 1997; Venville and Treagust, 1997), and (3) they can *motivate* students to learn meaningfully (Bean *et al.*, 1990; Lemke, 1990; Thiele and Treagust, 1994a; Dagher, 1995; Venville and Treagust, 1997; Glynn and Takahashi, 1998).

Cardinale (1993) claimed that analogical explication can enhance learning in situations where vocabulary is unfamiliar or concepts are complex and abstract. Analogies should therefore be particularly useful in biology, chemistry, and biochemistry instruction, where a lot of vocabulary is new for students, concepts are often challenging and/or abstract, and phenomena can be unobservable (Wood, 1990; Harrison and Treagust, 1996; Tibell and Rundgren, 2010).

Use of analogies in biology and chemistry classrooms

Analogies are a common teaching and learning tool in chemistry and biology courses and textbooks (Thiele and Treagust, 1994b, 1995; Thiele *et al.*, 1995; Tibell and Rundgren, 2010; Seipelt-Thiemann, 2012). In fact, Tibell and Rundgren (2010) state that the "language of molecular life science is characterized by the vivid use of metaphors" and that "metaphors and analogies are commonly used in molecular life science to facilitate 'visualization' of relevant concepts and processes" (p. 28). Both biology and chemistry instructors often share analogies they have found to be useful in practitioner journals. For example, in *The American Biology Teacher*, instructors have reported using chess as an analog to teach the role of animals in ecosystems

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(Kangas, 1988); a fireworks sparkler to represent the axon of a neuron (Griff, 2006); and different tools (*i.e.*, forceps, clothespins, chopsticks, *etc.*) as analogies for the beaks of Darwin's finches (Milne, 2008). From 1980 to 2009, a feature column focused on "Applications and analogies" was included in the *Journal of Chemical Education*. The goal of the column was, in part, to allow instructors to share useful classroom analogies to "increase understanding and retention time" of chemical concepts (De Lorenzo, 1980, p. 601). In that column, and in subsequent years, *Journal* contributors have shared analogies about different chemical and biochemical topics. For example, Gould (1999) described using telephone poles in order to help students understand phosphate buffers. Piepgrass (1998) used arcade games based on martial arts to explain collision theory. More recently, Hajkova *et al.* (2013) described the use of an egg carton to represent atoms on a chemical surface in a simulation of a scanning probe microscopy experiment. Although many analogies have been shared in the practitioner literature, they are most often presented in the absence of data on student learning outcomes.

Most of the limited number of studies that have examined the effects of analogy use in these disciplines suggests that students like analogies and that their scores on content-based tests increase after analogy-based instruction (see, for example, Baker and Lawson, 2001; Dicks, 2011; Seipelt-Thiemann, 2012); however, the biology and chemistry education literature also indicates that there are potential challenges associated with classroom analogy use. First, because analogies rely on students' understanding of a "familiar" analog domain and students enter a classroom with different prior knowledge, analogies are not equally well understood by all students. When students do not understand analogies, analogies are ignored, misinterpreted, or become extra information to learn (Thiele and Treagust, 1992; Venville and Treagust, 1997; Raviolo and Garritz, 2009). Take, for example, a student who was asked why ATP is referred to as cellular "currency." The student responded by saying that ATP provides electricity (current) for the cell. While, clearly, the student confused the meanings of "currency" and "current," further questioning revealed that the student did not understand what currency is and, for this reason, was unable to apply an understanding of "currency" to ATP (Orgill, 2003). Second, students may be unable to distinguish between the analog and target concepts and, thus, perceive the analogy as reality (Thiele and Treagust, 1995). Finally, and perhaps most importantly, every analogy is inherently limited in scope. Because of this fact, students can develop misconceptions when they inappropriately apply what they know about an analog domain to a target domain (Spiro *et al.*, 1988; Kaufman *et al.*, 1996; Venville and Treagust, 1997; Tibell and Rundgren, 2010). As an example, an instructor involved in this study described the interactions of substrates and enzymes as being similar to a hand fitting inside a glove. Although the instructor shared the analogy with the intention of helping students understand that enzymes adjust their shapes to accommodate a substrate (induced fit model), at least one student used the analogy to develop a picture of what enzymes and substrates look like (their shapes, their relative sizes, *etc.*).

However, enzymes do not look like gloves, and substrates do not look like hands. This misconception may have been a useful way for this particular student to think about enzyme-substrate interactions, but it is not correct (Orgill, 2003). Although, for the most part, analogies have been shown to support student learning in biology and chemistry, the challenges above suggest that they should be used with caution.

Use of analogies in biochemistry classrooms

Because biochemistry is a "child of two cultures, biology and chemistry" (Huang, 2000, p. 65), it is not surprising that analogies are also often used as a teaching and learning technique in biochemistry courses. It is not uncommon to find analogies in the journal *Biochemistry and Molecular Biology Education*, where instructors have reported using postage stamps to explain the cooperativity of hemoglobin subunits (Lydon, 2006), the cast of a play to represent a genome or a proteome (Pappas, 2005), and the removal of a latex glove to illustrate the ionization of amino acids (Schultz, 1997). Additionally, previously reported studies (Orgill, 2003; Orgill and Bodner, 2006, 2007) indicate that analogies are important teaching techniques in college-level biochemistry classes. Biochemistry students, for example, use analogies in a variety of ways to understand, remember, and visualize different biochemical concepts (Orgill and Bodner, 2007). Biochemistry textbooks also include analogies as an instructional technique. In fact, there are many more analogies in biochemistry textbooks than general science textbooks, secondary chemistry textbooks, or social science textbooks (Orgill and Bodner, 2006). Many terms with analogical roots have become so common that they have become part of the biochemistry lexicon. Take, for example, the facts that ATP is referred to as cellular "currency," that the structure of a cell membrane is described as a "fluid mosaic," that substrates and enzymes interact with each other like a "lock and key," or that proteins that assist with the assembly or disassembly of other molecules are called "chaperones."

Anderson and Schönborn (Anderson and Schönborn, 2008; Schönborn and Anderson, 2008) have identified analogical reasoning as an essential component of biochemists' "expert knowledge and skill competence" and as one of five cognitive skills that should be "formally taught and assessed as part of all biochemistry course curricula" (Anderson and Schönborn, 2008, p. 310). According to them, "because learning in biochemistry depends very heavily on understanding the abstract world of molecular structures and processes, developing analogical reasoning skills is absolutely crucial for becoming an expert biochemist" (Anderson and Schönborn, 2008, p. 312). Despite this fact, there has been very little research that has focused specifically on the use and effectiveness of analogies in biochemistry classrooms (see, for example, Orgill and Bodner, 2006, 2007).

If analogical thinking is a critical cognitive skill for expert biochemists and if analogies are important pedagogical and learning tools in biochemistry courses, the use of analogies in biochemistry classrooms merits additional consideration and

research. This might start with an examination of how biochemistry instructors perceive and use analogies in their courses, extends to a comparison between the use of analogies in biochemistry courses and analogical best practices identified in the literature, and continues with a testing of different classroom interventions and their influence on analogical transfer. Here, we explore the first of these issues: how analogies are currently being perceived and used in biochemistry courses.

Coll *et al.* (2005) state that “teachers [are] an important link for learners developing a more complex understanding and use of analogies and models” (p. 186). Therefore, as a first step toward improving analogy use in biochemistry classrooms, we need to examine how biochemistry instructors perceive analogies and their classroom use. In the section that follows, we review the existing literature about instructors’ perceptions of the use of analogies in science classrooms to provide a foundation for the current study.

Science instructors’ perceptions and use of analogies

There are very few examples in the research literature of studies that examine science instructors’ perceptions and use of analogies, and most of these studies focus on the perceptions of secondary science teachers. In the studies that have been reported, researchers have examined the perceptions of two main categories of instructors about the use of analogies in their classrooms: instructors who have had no formal instruction in analogy use and those who have. As might be expected, instructors who have no formal instruction in the use of analogies still use analogies in their classrooms (Oliva, 2003), and research has suggested that instructors believe they use analogies more often than they have been observed to do so (Treagust *et al.*, 1992; Thiele and Treagust, 1994a).

Previous research has also shown that instructors identify specific reasons for using analogies in their classrooms. Moreover, as their teaching experience increases, their reasons for using analogies become more sophisticated. Student teachers state that they use analogies either to help students understand difficult topics or to entertain students (Jarman, 1996). More established teachers say that they use analogies not just to promote learning and understanding of difficult or abstract concepts (see, for example, Harrison and De Jong, 2005) but also to engage students and give them ownership over their learning (Taber *et al.*, 2006), to help students overcome misconceptions, or to help students visualize different concepts (Treagust *et al.*, 1992; Harrison and De Jong, 2005). Harrison and De Jong (2005) noted that the established Grade 12 teacher they observed, Neil, liked using analogies because “they are interesting and provoke discussion. At the same time, he wanted to impress on the students that an analogy is always artificial, and he wanted them to find the flaws, to find where the analogies break down because, in his opinion, all analogies have limitations” (p. 1140).

Interestingly, although many of the instructors who have been interviewed about their use of analogies in secondary science classrooms mentioned that it is important to explicitly point out the limitations of analogies to their students, they rarely do so in

practice (Treagust *et al.*, 1992; Thiele and Treagust, 1994a; Jarman, 1996; Oliva, 2003; Harrison and De Jong, 2005; Taber *et al.*, 2006).

When instructors use analogies in their classrooms, they say that they do not use them as the first method of explanation (Thiele and Treagust, 1994a). Instead, they rely first on direct explanations, only using analogies if their students look confused after the initial explanation. Because analogies are not the primary method of instruction, instructors indicate that they do not plan or write down the analogies they use in their classrooms (Thiele and Treagust, 1994a; Oliva, 2003). In fact, classroom use of analogies is reported as being “frequently idiosyncratic” (Coll *et al.*, 2005, p. 187).

Instructors do not always explain the mappings between the analog and target concepts they use (Thiele and Treagust, 1994a; Jarman, 1996; Oliva, 2003), even though this strategy is known to support student learning from analogies (Harrison and Treagust, 1996). Jarman (1996) noted that student teachers could not see any reason for including such an explanation; they considered a simple statement of the analogy to be a sufficient explanation of a given target concept. In another study, Thiele and Treagust (1994a) found that more experienced instructors did not always explain their analogies either, but they often supplemented their analogy explanations with a pictorial component. As one of the teachers interviewed in that study noted, she “used pictorial analogies as an aid for the students’ imagination and because it helped her to express what she saw in her own mind, which she believed to be pictorial” (pp. 234–235). The fact that experienced teachers in the Thiele and Treagust (1994a) study often used pictorial representations of analogies may have been an anomaly, however. Mastrilli (1997) observed eight inservice biology teachers who had at least five years of teaching experience. He found that teachers did not often use visual aids to supplement their presentation of analogies.

More experienced teachers also tended to monitor students’ understandings of teacher-provided analogies by quizzing students about connections between analog and target domains (Harrison and De Jong, 2005; Taber *et al.*, 2006; Oliva *et al.*, 2007). This allowed the teachers to monitor not only students’ understandings of the analogy itself, but of the target concept the analogy was meant to teach. This is a strategy employed by Neil, the Grade 12 teacher mentioned earlier. According to the researchers, “Neil sees the use of his analogical models as a process that connects his and his students’ dynamic experiential memories. The analogy is an instance where he and the students can interact by mapping their everyday knowledge onto the concepts he knows that they need to understand” (Harrison and De Jong, 2005, p. 1145).

Only one study has reported the results of interviews done with instructors who have been trained in analogy use. For the most part, their responses are similar to those of the instructors who have not been trained in analogy use. There is, however, one major difference. The instructors who had been trained in analogy use *did* mention the limitations of the analogies they used to their students, and none of them felt that the time required to do this was excessive (Harrison and Treagust, 1994).

Comments from their students indicated that the students felt more comfortable with an analogy if their instructor mentioned the limitations because they were unable to identify these limitations on their own.

In all of the aforementioned studies except for one, classroom analogies were exclusively teacher-driven and teacher-provided. Although teachers were willing to monitor students' understandings of analogies, they did not involve students in the co-construction of knowledge through the creation of analogies, or even use analogs that came from experiences more common to students (Thiele and Treagust, 1994a; Oliva, 2003; Oliva *et al.*, 2007). In only one case (Taber *et al.*, 2006) were students asked to develop their own analogies and then compare them to a model scientific answer, a process which revealed their own understanding of the target concept.

Purpose of the current study

The purpose of the current study was to answer the research question: "What are biochemistry instructors' perceptions of analogies and their use in biochemistry classes?" The main data source for the study was interviews with biochemistry instructors. A secondary source of data was observations of analogy use in the classrooms of some of the instructors who were interviewed. The observational data is not the main focus of this article; it is used to provide perspective on the perceptions of the instructors.

Methodology

Qualitative research of this nature must be based on a theoretical framework or perspective (Bodner, 2004). We chose phenomenography as the theoretical framework for this study because the authors' experiences as both students and instructors of biochemical concepts have led us to believe that instructors have a variety of ways of perceiving and using both specific biochemistry analogies and analogies in general. 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; Orgill, 2007). Its objective is to define the different ways in which people experience, interpret, understand, perceive, or conceptualize a phenomenon or certain aspect of reality.

In order to determine how instructors perceive the use of analogies in their classrooms, we observed college-level biochemistry classes and interviewed biochemistry instructors. We received permission to observe five different semester-long biochemistry courses at a large Midwestern university, each taught by a different instructor. They included one introductory biochemistry class for freshmen ("100-level biochemistry"), one introductory biochemistry class designed for majors from a school of agriculture ("300-level biochemistry"), one introductory biochemistry class designed for a mixed upper-level undergraduate/graduate-level population ("500-level biochemistry"), and two graduate-level special topics courses in biochemistry ("600-level special topics" and "700-level special topics"). The first author

attended each lecture with the exception of the days on which tests were given or when she was ill. In class, she used a modified version of the "Analogy Classification Framework" (Thiele and Treagust, 1994b; Orgill, 2003; Orgill and Bodner, 2006) to record the circumstances under which the analogy was used in the class (*i.e.*, was the analogy presented verbally or pictorially?, was the analog concept explained?, to what level of depth was the analogy explained?, was the analogy identified as an "analogy"?, were the limitations of the analogy explicitly identified?, *etc.*). She also took written notes about the presentation of each analogy. Immediately after class, she wrote a rich narrative description of the analogy and its classroom presentation. We believe that our semester-long observations have allowed us to develop a more accurate representation of how analogies were used by each instructor than we would have been able to develop after participating in a limited number of class periods. Although not the main focus of this study, our observations provided topics for discussion during interviews with the biochemistry instructors and a perspective for interpreting their responses.

We interviewed biochemistry instructors who had experience teaching an introductory biochemistry course. We first asked for volunteers from the instructors whose classes we had observed. Drs Williams, Carter, and Brown (all instructor names are pseudonyms), the instructors of the 100-, 300-, and 500-level introductory courses, respectively, agreed to be interviewed. We asked these three instructors to suggest colleagues from their departments who use analogies and who have taught introductory biochemistry. Two of these instructors agreed to be interviewed when we contacted them (Drs West and Thomas). Finally, we contacted biochemistry instructors at three different colleges and universities in the Midwest. Eight instructors from these schools agreed to meet with us: one instructor from a small liberal arts college (Dr Allen), four instructors from a mid-size, primarily undergraduate university (Drs Horn, Castle, Owen, and Banks), and three instructors from a mid-size state university (Drs Smith, Waters, and Nelson). Overall, we conducted interviews with a total of thirteen biochemistry instructors. Table 1 lists the pseudonyms for each of the interviewed instructors, along with their institution types and the level of introductory biochemistry courses they taught. For the instructors whose courses were observed, only the course they taught the semester they were observed is listed. For the instructors whose courses were not observed, all introductory biochemistry classes they had taught previous to their interviews are listed. It should be noted that the only instructors included in this table are those who agreed to be interviewed since their interview transcripts comprise the main data source for the current study; instructors whose courses were observed but who did not agree to be interviewed are not included in the table because data from their courses was not the main focus of this study or was examined in aggregate with the data from other observed courses.

All interviews were semi-structured and conversational in style, lasting approximately one hour each. We began each interview by asking instructors to tell us about their educational and teaching background, continued by asking instructors about

Table 1 Instructor pseudonyms, along with their institution type and the level of introductory biochemistry courses they taught^a

Instructors whose courses were observed		
Dr Williams	Large University	100-level Introductory Biochemistry for Majors
Dr Carter	Large University	300-level Introductory Biochemistry for Nonmajors
Dr Brown	Large University	500-level Introductory Biochemistry for Majors
Instructors whose courses were not observed		
Dr Allen	Small Liberal Arts College	300-level Introductory Biochemistry for Majors
Dr Banks	Mid-size Primarily Undergraduate Institution	200-level Introductory Biochemistry for Nonmajors
		400-level Introductory Biochemistry for Majors
Dr Castle	Mid-size Primarily Undergraduate Institution	200-level Introductory Biochemistry for Nonmajors
Dr Horn	Mid-size Primarily Undergraduate Institution	200-level Introductory Biochemistry for Nonmajors
		400-level Introductory Biochemistry for Majors
Dr Nelson	Mid-size State University	300-level Introductory Biochemistry for Majors
Dr Owen	Mid-size Primarily Undergraduate Institution	200-level Introductory Biochemistry for Nonmajors
		400-level Introductory Biochemistry for Majors
Dr Smith	Mid-size State University	200-level Introductory Biochemistry for Nonmajors
		300-level Introductory Biochemistry for Majors
Dr Thomas	Large University	300-level Introductory Biochemistry for Nonmajors
		500-level Introductory Biochemistry for Majors
		500-level Introductory Biochemistry for Medical Students
Dr Waters	Mid-size State University	200-level Introductory Biochemistry for Nonmajors
		300-level Introductory Biochemistry for Majors
Dr West	Large University	500-level Introductory Biochemistry for Medical Students

^a For the instructors whose courses were observed, only the course they taught the semester they were observed is listed. For the instructors whose courses were not observed, all introductory biochemistry classes they had taught previous to their interviews are listed. It should be noted that the only instructors included in this table are those who agreed to be interviewed since their interview transcripts comprise the main data source for the current study; instructors whose courses were observed but who did not agree to be interviewed are not included in the table because data from their courses was not the main focus of this study or was examined in aggregate with the data from other observed courses. The course levels indicated are those identified by the instructors; course levels may vary from school to school.

analogy use, and finished by asking instructors to identify and comment on the specific analogies they use in class. The complete interview guide can be found in Appendix A.

We transcribed each of the interviews verbatim. Based on an initial reading of the transcripts and their knowledge of the literature, the first two authors identified themes they felt merited further analysis. They chose to examine transcripts for evidence of instructors' perceptions of the following: (1) why analogies are generally useful to learning, (2) why they choose to use analogies in class, (3) where they find the analogies they use in class, (4) how they plan the analogies they use, (5) the advantages of using analogies, (6) the disadvantages of using analogies, (7) when analogies should be used, (8) how analogies should be presented to be effective, (9), what kind of students benefit from analogies, (10) how students use analogies to learn, and (11) what instructors should do to help students learn from analogies. The first and second author independently coded each of the transcripts, making a list of categories—supported by evidence from the transcript—under each theme (e.g., specific reasons instructors use analogies) while, at the same time, looking for evidence of themes that had not been initially considered. No additional themes manifested during this analysis. Discussion of the codes led to the removal of themes for which there was no supporting evidence in the transcripts (Themes 7, 9 and 10 above). Other themes were grouped because instructors did not distinguish between them in their responses to interview questions (Themes 1, 2, and 5; Themes 3 and 4; and Themes 8 and 11). Over multiple meetings, the first two authors met to discuss their combined categories under each theme group. During those meetings, they developed

common language to describe the categories, coming to consensus on each category description. As a final level of analysis, they developed five theme-based assertions, each of which describes how biochemistry faculty perceive analogies and their classroom use. In the sections that follow, we provide supporting evidence for each of these assertions.

Results and discussion

Assertion 1

Biochemistry instructors use analogies in their classrooms, even if they aren't sure when or whether they use them.

All of the instructors we interviewed said that they use analogies in class. While some instructors immediately recognized and indicated that they use analogies liberally, others stated that they rarely use analogies.

Interviewer: Do you feel like you use [analogies] when you teach?

Dr West: Oh... all the time. I don't think you could teach without analogies. I mean, I think analogies are how we learn, no matter what the topic is. You can only learn if you can relate it to something else, and I think that's what you use. You do use analogies. How is this compared to something that I already know? If you can't put things in context, it's just going to be words.

When asked a similar question during his interview, Dr Nelson responded that, although he uses analogies, he does so only rarely and always without prior planning or intention:

Dr Nelson: I don't use them as a rule, no. And like I said, I've never planned to use an analogy during class. I've never made

up a slide or an overhead to show the class an analogy. Never done it. Maybe I should.

Most instructors simply said that they know they use analogies but are not aware of how often they use the analogies. Each instructor, though, believes that analogies are useful in teaching situations. In fact, all of the instructors who initially said that they do not use analogies eventually recalled analogies that they had used in their classes. One instructor even stated his belief that the best instructors are those who use analogies.

Dr Castle: I think the better teachers are the ones who are good at analogies. [...] I think when I look at our department, the people that are really good at telling stories are also very good at educating the students in the ideas and concepts. They can hold a student's attention. They can still teach the material; and they're not just entertainers, they're educators.

We found it interesting that the instructors' actual use of analogies and their perceptions of analogy use were not always consistent. For example, the first author observed the classes of three of the instructors we interviewed. Two of these instructors used many analogies in their classes, and one of them used very few. The instructor who did not use many analogies in his class perceived, accurately, that he did not use many analogies. One of the instructors who used a lot of analogies stated that he does use many analogies, but that he did not recognize that fact until we began speaking about the analogy use in his class. The other instructor who used many analogies in his class said that he does not feel like he used analogies often.

The results of this study are consistent with those of previous studies (Treagust *et al.*, 1992; Thiele and Treagust, 1994a) in that biochemistry instructors use analogies, but they do not overuse analogies. We recorded 110 unique analogies in the five courses we observed. Examples of the analogies used in the 100-, 300- and 500-level biochemistry courses are presented in Table 2. Many more unique analogies were used in the freshman biochemistry class than in either the junior-level introductory biochemistry class or the three graduate-level classes. We observed 47 analogies (1.74 per class period) in the 100-level class; but only 20 (0.56 per class period), 15 (0.38 per class period), 15 (0.39 per class), and 13 (0.24 per class period) analogies in the 300-level, 500-level, and two special topics classes, respectively.

The general trend in the data is that biochemistry instructors use more analogies in lower-level classes than in higher-level classes. This trend was even more apparent when we looked at the percentage of class-hours over the semester in which an analogy—whether a unique analogy or re-presentation of a previously used analogy—was used. Roughly 75% of the 100-level class-hours contained at least one analogy. Similarly, 53%, 35%, 26%, and 27% of the 300-level, the 500-level, and the two special topics biochemistry class-hours contained at least one analogy.

Jarman (1996) indicated that student teachers' use of analogies depended on their personal teaching styles and their perceptions of the abilities of their students, with the student teachers using more analogies with students they perceived as being of lower ability. As noted previously, similar results were obtained in this study of biochemistry instructors. When we spoke with the instructors about this trend, they expressed beliefs that

undergraduate students need analogies to learn more than graduate students do.

As had been seen in previous studies, all of the analogies we observed and all of the analogies discussed by the participants were teacher-provided. None of the observed classes involved students in the construction of an analogy. Two of the instructors mentioned that it might be worthwhile to have students participate in creating an analogy, but these instructors also stated that they did not know how to create or assess an assignment in which students generate analogies. Our results therefore suggest that biochemistry instructors mainly see analogies as something to be learned instead of as a means of constructing knowledge.

Assertion 2

Biochemistry instructors use analogies for a variety of purposes to promote student learning.

The biochemistry instructors we interviewed indicated that analogies were useful for biochemistry teaching and learning. They identified the following specific reasons they choose to use analogies in their courses: (1) to help students learn difficult biochemistry concepts more easily, (2) to help students make connections between what they already understand and the biochemistry concepts they are learning, (3) to help students visualize abstract concepts, (4) to engage and interest the students, and (5) to provide a framework for understanding biochemical phenomena.

Biochemistry instructors use analogies to help students develop understandings of difficult concepts. The primary reason that the instructors said that they use analogies in their classes is to make difficult biochemistry concepts easier to learn. Analogies, according to the instructors, make learning easier in two specific ways. First, analogies provide an alternate explanation of a concept, which is particularly useful when students have not understood a more direct explanation. Dr West commented that finding alternate ways of presenting information was one of her goals in teaching, and analogies help her do that: "What you do when you're teaching is trying to provide a variety of different analogies in case what was in the book didn't connect." This was the case in Dr Brown's 500-level biochemistry course. His students were having difficulty understanding the cooperativity of hemoglobin subunits. They did not understand how the binding of oxygen at one subunit would affect the conformation of another subunit of the protein. To help his students understand this concept, Dr Brown compared the effects of oxygen binding to hemoglobin to two different scenarios. First, when a fly gets caught on a spider web, the spider can feel that the fly is stuck even though the spider is not next to the fly. The changes in the shape of the web that occur when the fly becomes stuck to the web transmit the signal to the spider on another part of the web. Second, and similarly, if a baseball hits a chain-link fence, the disturbance of the collision (that the fence is temporarily bent when the ball hits) is transmitted through the rest of the fence (even though the rest of the fence was not hit by the ball). The students seemed to understand the analogical explanation better than they had understood the original, more technical one.

Table 2 Examples of analogies used in the 100-, 300- and 500-level introductory biochemistry courses

Course level	Target concept/analog concept	Description of classroom use of analogy
100	Limits on cell size/limits on campus size	Dr Williams was talking to the students about the sizes (relative and actual) of molecules, organelles, cells, <i>etc.</i> He asked the students, “what is it that limits the size of this campus?” Eventually, the answer came that the size of the campus was limited by the distance that a student can walk from back to back classes in 10 minutes (the passing period). He said that the size of a cell is limited in the same way: by the amount of time that it takes for materials to be transported across the cell. The cell can only be as big as the distance that materials can travel before they need to be used. He then mentioned that eukaryotic cells are larger than prokaryotic cells because they are more organized. He said that cells need materials to be transported across them quickly, so prokaryotic cell size is limited by the distance that molecules can diffuse in that short time, just like the size of the campus is limited by the distance that students can walk in the passing period. Eukaryotic cells, however, are more organized and can trap large concentrations of molecules inside organelles where they need to be used. Therefore, their sizes are not limited as much by diffusion time.
100	Amino acids in a peptide/elephants	Dr Williams compared amino acids to elephants. Elephants have a trunk on one end and a tail on the other, which can be used to connect them together in a chain. Likewise, an amino acid has an amino group on one end and a carboxyl group on the other end that can be used to link them together. If you have a line of elephants linked trunk to tail, there will be one elephant with an unoccupied trunk and one elephant with an unoccupied tail. Likewise, a protein has one amino acid with an unoccupied amino group and another with an unoccupied carboxyl group.
300	Induced fit model/putting a hand in a glove	Dr Carter compared the induced fit model to a hand fitting in a glove. He said a glove is not a perfect fit for the hand, but it accommodates your hand, like an enzyme accommodates its substrate.
300	Determining whether a reaction will occur/determining if a student will eat a certain food	Dr Carter told the students that the spontaneity of a reaction depends on the conditions under which a reaction takes place. He asked the teaching assistant (TA) to stand up. Dr Carter said that he had noticed that the TA has a healthy appetite and asked him if he likes tofu (no) and if he likes pizza (YES!). Dr Carter then asked the TA, “if you were on a deserted island and had no food and a crate of tofu washed up on shore, would you eat it?” (Yes!) “What about if your mom made a big spread and you’ve just eaten a lot of food? Do you still want to eat pizza?” (no) “So, whether or not you eat pizza or tofu depends on the conditions. Similarly, whether a biochemical reaction is spontaneous or not depends on the conditions under which the reaction takes place.”
500	Equilibrium of chemical reactions/a series of connected pipes	Dr Brown drew a picture on the overhead of two pipes/cylinders connected to each other by a turbine (together, the pipes formed a U shape with a turbine at the center of the base of the U). He then explained: “if there is water in only one of the pipes, we know that the water will naturally flow until both pipes have equal amounts of water in them. The flow of water through the turbine will generate energy or work. If, however, the starting situation is that of equal amounts of water in each of the pipes, there will be no net flow of water and no work generated. Similarly in chemical reactions, systems at equilibrium do no work.” After giving this comparison, Dr Brown continued by referring back to the original U-shaped pipes. “The amount of work we get out of this system will depend on how high the water is in one pipe compared to the other. In chemical reactions, the quantity of work you get depends on how far the reaction is away from equilibrium to start out with.” Dr Brown then made the statement that hardly any biochemical reactions (in living organisms) are at equilibrium.
500	Regulation of metabolic pathways/a series of pipes with valves or constrictions	Dr Brown talked about how the regulation of one enzyme in a pathway could affect the rate of an entire biosynthetic pathway (<i>i.e.</i> , how the regulation of the rate-determining step could affect the rate of an entire metabolic pathway). He compared this to a pipe with a constriction in it. The flow of water through the pipe is determined by the diameter of and flow through the smallest part of the pipe. If we put a valve at the smallest part of the pipe, we can control whether or not water flows past that point of the pipe. It is the same with enzyme pathways. There are control enzymes (rate-determining steps) which control the “flow” of enzyme products to the rest of the pathway. Dr Brown then applied this analogy to glycolysis, in which phosphofructokinase (PFK) is the enzyme that catalyzes the rate-determining step. He compared PFK to a valve on a pipe. If the pipe delivers ATP (the pipe would be the glycolysis pathway in this case), the valve (PFK) will be turned on when ATP is needed and off when ATP is not needed.

Second, because the concepts and phenomena discussed in a biochemistry concept are abstract and complex, the language used to describe those phenomena is also abstract and complex. Several instructors indicated that analogies provided a more “friendly” means for communicating scientific concepts. Dr Banks, for example, saw analogies as a way to make biochemistry concepts less intimidating.

Dr Banks: I think that chemistry can be very unfriendly for students and very abstract, and so I do think if there's something, as I say, that helps to give them a better feel for

what's actually going on... I used to have a math teacher, you know, differential equations, and he would say, ‘given an epsilon greater than delta, you would find blah, blah, blah this, that derivative,’ and then he'd say, ‘let me tell it to you in street talk’; and, all of a sudden, when he did it in street talk, it became clear. And I think street talk is something you need in chemistry, especially for the non-majors because it is very intimidating and very abstract. So, if the analogies can take something from a very formal type of approach to street talk where somebody can actually understand us... if it helps in understanding, then I'm all for it.

Biochemistry instructors use analogies to help students make connections between what they already know and the biochemistry concepts they are learning. Most of the instructors we spoke with said that biochemistry is a difficult topic to learn because students are not able to relate what they are learning to what they already understand, whether that be a concept from a previous course or a concept from the students' everyday lives. The instructors wanted their students to understand biochemical concepts in the context of previously learned knowledge instead of simply memorizing them, and instructors believe that analogies help students do that. When asked "When do you choose to use analogies in your class?," Dr Nelson responded as follows:

Dr Nelson: Even scientists don't... or students who are science majors... don't think in science terms every day. [...] It's not natural for them to visualize a scientific process in their mind because they haven't done it enough; but they've had real world experiences their whole life, so, often, if you can make that link of something that's commonplace to them and then link that commonplace experience to a scientific example, which is not natural, maybe will help make that leap.

Dr Carter often used analogies to relate biochemical knowledge to everyday activities and objects. For example, he used an elaborate analogy to explain the properties and modifications of nucleic acids in his 300-level biochemistry course. He told the students that he believed that DNA was very much like a recipe. He asked the students to imagine that they are members of a family that owns a restaurant. The family has an archival cookbook that contains all of the recipes (the DNA) that are made in the restaurant (the cell). He said that, on some nights, you may only want to make a subset of recipes. In that case, then, you can photocopy just the recipes you need. (An organism only transcribes the DNA that corresponds to the proteins it needs at a given time.) You can even make multiple copies of a recipe from the archival cookbook if you need a lot of a particular recipe and want multiple chefs working on making it at the same time. (An organism can make multiple mRNA copies of the same piece of DNA to be translated simultaneously by multiple ribosomes according to the need for a particular protein at a particular time.) What if one particular chef wants to change a recipe? He might change the ingredients on the recipe. You don't want his changes to be passed on to future generations, so it would be better for him to work with a copy of the recipe than the original cookbook. (An organism can modify RNA without modifying the DNA from which it was transcribed.) What if the cook drops the copy of the recipe in the sauce? If he drops a copy in the sauce, you can always make another copy from the archival cookbook later on. (If RNA is damaged, another RNA copy can be made from its corresponding DNA.) Dr Carter's analogy provided a consistent, familiar touchstone that the students could use to build their understanding of nucleic acids over the course of multiple class periods. For example, later in the semester, Dr Carter discussed upstream regions of DNA (promoters) that allow RNA polymerases to find genes that will be transcribed. He compared promoter regions to tabs on the side of cookbook that allow you to quickly find recipes.

Biochemistry instructors use analogies to help students visualize abstract biochemical entities and processes. Many instructors

that we interviewed said that biochemistry is also difficult to learn because it focuses on concepts, entities, and processes that students cannot see. Accordingly, these instructors used analogies as a way of helping their students visualize biochemical concepts and processes.

Dr Owen: Well, like I always tell my students, learning chemistry would be easy if you could see atoms because, as it turns out, much of what we do is really pretty simple; but what makes it hard is that you have to, then, deal with concepts that are invisible, yet at the same time, they're real. They're real things, and yet we can't see them, and so we have to be able to use our imaginations. [...] So, the idea of analogies is that what we are trying to show is that they actually already know this stuff. They actually... this is something that they already know because it's stuff they deal with every day at a conceptual level, and if one could see it, then it would be as easy as these other concepts that are trivial. [...] The analogy helps them to see that they're not really learning anything new, and they're just doing things that are obvious to a five year old if you could see atoms.

Dr Williams, for example, determined that it was difficult for his 100-level students to understand how amino acids that are not close in the primary structure of a protein may end up close to each other in a protein's three-dimensional structure. He compared a protein chain to a garden hose. The two ends are very far apart from each other when the hose is stretched out. However, when the hose is looped up, the ends become closer to each other and parts of the hose that were not close to each other before become closer. Dr Williams found the garden hose analogy to be a useful way to help his students visualize the three-dimensional characteristics of proteins.

Nearly all of the instructors we interviewed said that they use analogies to help students visualize biochemical concepts. It seems reasonable, then, to think that instructors would use some sort of external representation during their presentation of analogies; however, the classroom observation data shows the opposite. Of the 110 unique analogies we observed in five different classes, the majority were presented verbally. Only 16 analogy presentations included an external representation of either the analogy or of the analog concept, and nine of these occurred in the 100-level biochemistry course. Very few pictorial representations of analogies were observed in the other courses, consistent with what has been observed in other studies of both science courses and textbooks (*e.g.*, Curtis and Reigeluth, 1984; Thiele and Treagust, 1994b; Thiele *et al.*, 1995; Mastrilli, 1997).

That biochemistry instructors are not using external representations to supplement their presentation of analogies is somewhat disconcerting, as previous research has shown that the use of a picture decreases the likelihood that a student is unfamiliar with an analog concept (Thiele and Treagust, 1992; Orgill and Bodner, 2004), decreases the chance that students will misinterpret an analogy (Orgill and Bodner, 2004), and increases understanding and retention of target concepts (Beveridge and Parkins, 1987; Bean *et al.*, 1990). It may be that biochemistry instructors either do not understand the importance of including an external representation of an analogy or that they believe students are capable of forming their own

mental images of the analogies are presented to them. This is a subject for future research.

One other issue related to analogy use and visualization in biochemistry warrants further consideration. Recent research has documented the difficulties that students encounter when attempting to interpret external representations of biochemistry concepts (Schönborn *et al.*, 2002; Schönborn and Anderson, 2006; Harle and Towns, 2012a, 2012b; Linenberger and Bretz, 2012). Studies from this body of research emphasize that students' interpretations of external representations are influenced by their prior knowledge (Schönborn and Anderson, 2009; Harle and Towns, 2012a, 2012b). Analogies can be part of students' prior knowledge and can, therefore, influence their interpretations of external representations. For example, Schönborn and Anderson (2009) examined students' interpretations of an external representation of Immunoglobulin G (IgG). They found that several students correctly—and incorrectly—applied their understanding of the lock-and-key model of biomolecular interactions to describe interactions between an antibody and an antigen. The students correctly indicated that interacting antibodies and antigens should have complementary shapes. However, they incorrectly extended their understanding of the lock-and-key model to conclude that an antibody can only interact with one antigen at a time. According to Schönborn and Anderson (2009).

“For enzyme–substrate reactions, typical lock-and-key ERs [external representations] usually show the simple situation of a *single* enzyme binding to a *single* substrate. When applying the analogy to the context of antibody-antigen binding it is possible, therefore, that students may have thought that each IgG molecule can only bind one rather than two antigen molecules” (p. 210).

In this case, students' prior knowledge of a common biochemistry analogy affected their abilities to correctly interpret an external representation. Given the evidence from the Schönborn and Anderson (2009) study it seems that the influence of analogies on students' biochemical visual literacy should be further examined.

Biochemistry instructors use analogies to engage their students. The instructors with whom we talked realized that students learn more meaningfully when they are engaged and interested in their learning, so they use analogies for that purpose. Dr Carter, for example, saw the analogies he uses in class as a means to gain students' attention and involve them in learning biochemistry concepts.

Dr Carter: An analogy is not a way of drilling a hole in someone's head... pouring information in. You can't do that. You cannot physically do that, but you can engage them, and you can provide them with some sort of a tool to help them learn.

Biochemistry instructors use analogies to provide a framework for understanding biochemical phenomena. With one exception, the instructors we interviewed saw analogies as a purely pedagogical strategy, one that they could use in a classroom to help their students develop better understandings of biochemical concepts. One instructor, however, stated his belief that analogies are often used in scientific research to

provide a framework for organizing our current understanding of a concept, to give us a new way of viewing a concept, to allow us to communicate about a concept, or to allow us to develop hypotheses about a given concept. One of his purposes for using analogies in his classroom, then, was to give students a way to think about and question a biochemical concept they were learning. He saw this process as part of “scientific thinking.”

Dr Williams: At some stage of, of learning where we're at the frontier [of our understanding], we've got to develop some sort of a physical construct that allows us to visualize what might be happening, so that we can talk to others about it and so that we can develop hypotheses that might be tested. You see that all the time in science where... here's this structure, you know, you've got circles and squares and things that come in and something goes over here. It's not reality. Oh, sure, they'll have a DNA piece in there, and they'll show a double helix, but it's not reality. And, yet, it does help as we're trying to figure out, ‘how do I explain what's going on inside this cell to myself and to others’... and we're all going to agree that this is a cartoon, this is not reality, but it helps us organize the world we're working on into a framework that we can use to probe, to get somebody else to react to, to communicate our level of understanding about it. So, maybe those kinds of analogies are useful whenever we are at the frontier of our knowledge.

Assertion 3

While biochemistry instructors are aware of many potential benefits of using analogies in their classrooms, they seemed less aware of potential disadvantages or challenges associated with analogy use.

Although many of the instructors with whom we spoke identified multiple advantages of analogy use, they were less able to identify potential disadvantages or challenges associated with analogy use. When they were explicitly asked to discuss them, they focused on three main disadvantages of analogy use: (1) analogies may not be understood correctly, (2) analogies may distract students from focusing on the “real” course information, and (3) the use of analogies requires a lot of class time.

Students may not understand the analogy. The first potential disadvantage of analogy use identified by the biochemistry instructors was the fact that students might not understand the analogy. Instructors realized that students come into their classrooms with different experiences and backgrounds. For this reason, they may not be familiar with the analog domains chosen by the instructors and, as a consequence, they may not understand the instructors' analogies. Dr Williams comments on this fact.

Dr Williams: The analogy or example you pull out may resonate with student A and may not resonate with student B. If you've never seen cattle huddling together in a snow storm or in a blue norther [a specific type of cold front that moves through the state of Texas], which we used to have down in Texas, what good is that example? ‘Well, what do you mean?’ Lots of things, if you've never seen them, and I try to use it as an example or an analogy, it will mean nothing.

Instructors also realized that some analogies are more accessible to students of a certain cultural/language background or a certain gender. Multiple instructors, including Dr Carter, commented on this fact: "Many analogies that I'm familiar with have to do with mechanics, and there may be a significant bias when gender... so the accessibility to that information." Although the instructors realized that some of their analogies were biased toward one gender or one cultural group over another, none of them was taking steps to address this bias. Instead, instructors used analog concepts and analogies that came from their own backgrounds instead of from their students' backgrounds, which is consistent with what has been observed in previous studies (Thiele and Treagust, 1994a).

Even when students are familiar with the analog concept provided by the instructor and seem to understand the analogy, students can take the analogy too far and develop misconceptions based on the analogy (see, for example, Thagard, 1992; Venville and Treagust, 1997). This was a potential disadvantage mentioned by each of the instructors we interviewed, including Dr Owen:

Dr Owen: Another problem [...] is that all analogies, at some point, break down. [...] And if you carry an analogy too far, then you get yourself into trouble, so, usually, only certain aspects of the common, familiar concept which you're analogizing will work, and other aspects of it will not work, and you have to know when to stop.

Although instructors were quick to recognize that all analogies have limitations and, thus, can be misinterpreted, they were also quick to say that they did not anticipate that students would develop misconceptions from analogies. They saw students as intelligent beings who should be able to identify where an analogy breaks down and then not take the analogy too far. Research indicates, however, that students can lack sufficient content knowledge to be able to identify the limitations of an analogy (Holton, 1984; Harrison and Treagust, 1994, 1996).

Students may be distracted by the analogy. Another potential disadvantage of analogy use is that students may think they understand an analogy so well that they are distracted by the analogy and focus on it instead of focusing on the biochemical information the analogy is meant to convey.

Dr Carter: Somebody once told me that I explain things so clearly, I convince students that they understand things that they don't. What a backhanded compliment that is [...] If a student goes and understands an analogy, it might persuade them to not bother to learn the real facts, so to be content with the understanding of the analogy, and that's never my objective.

Many instructors commented, in a similar fashion, that their intent of using analogies was to help students to learn biochemistry concepts, not to help them learn an analogy. They did notice, though, that some of their students tend to equate the analogy with reality.

Dr Williams: The analogy becomes reality for them [...] It strikes me as a danger of using analogies if they take [the analogy] for reality as opposed to just a way of thinking about reality that helps illumine, [...] that helps to shine light on reality, help us come closer to understanding.

Analogies may waste class time. Instructors also identified some very practical disadvantages associated with using analogies in class. The first of these is simply that presenting analogies takes time; and time is often at a premium in a biochemistry class. Dr Nelson summarizes the thoughts of many of the instructors we interviewed.

Dr Nelson: Now, I may be wrong about this, so maybe I shouldn't say it, but maybe... I maybe think of it, in a selfish way... it's a time constraint. It takes a lot of time to work your way through both the real world explanation and the scientific explanation and try to bridge the gap between the two; and, in biochemistry, we cover a lot of material, and we tend to be very selfish about our lectures. We want to get through the material. I don't want to deprive students of any topic in biochemistry. So, we tend to move very fast, and I think it takes a lot of time out of my lecture, so that may be a disadvantage.

The first practical disadvantage to the use of analogies comes from the instructor's perspective: analogies take time away from *teaching* additional content. The second practical disadvantage comes from a student's perspective: presenting an analogy for a concept students already understand is a waste of the students' class time. Dr West commented on this possibility: "If you use analogies for things that people already know, you're wasting their time; and people are very conscious of that."

Additional concerns. Instructors mentioned two additional concerns about using analogies that were not brought up by any of the other biochemistry instructors we interviewed but that were interesting, nonetheless. Dr Nelson, mentioned that analogies might change the way his students view him. More specifically, he worried that students would not think that he was serious about science content if he used analogies: "I think you run the risk of coming off less serious about the science and the material if you use too many analogies." This comment is interesting because it does not correlate with student comments. In a previous study (Orgill and Bodner, 2007), we interviewed biochemistry students about the analogies used in their courses. The students commented that they liked it when their instructor used analogies because it made the students feel like the instructor cared about them and their learning.

Another professor mentioned, as a side-note, that, because many analogies are teacher-generated, the use of analogies in class does not always support active learning strategies. Dr Allen was the only instructor to voice this concern: "[Analogies are] teacher-generated, not student-generated, so they're not as active a learning thing." This led us to believe that instructors may not be aware of how analogies can be used as part of an active learning strategy, but this assumption will need to be verified through future research.

Assertion 4

Overall, biochemistry instructors perceive that they use analogies mainly to explain concepts students find difficult to understand. While most of the analogies biochemistry instructors use are spontaneously developed in response to perceived student confusion, others are meticulously planned to address student difficulties.

Some of the questions we asked the biochemistry instructors during their interviews probed the origins of the analogies they use in class. Did they develop analogies intentionally? Did they read about them in a book? Did they learn them from a colleague? Without exception, the biochemistry instructors we spoke with said that the majority of analogies they use in class were, at least initially, developed spontaneously in class in response to a student's question or confused look. If those analogies went over well with students and were remembered by the instructor, the analogy might get woven into a subsequent class's lecture; but the analogies were initially developed on the spot to address student confusion about a difficult concept. Consider the following quotations from interviews with Dr Nelson and Dr Owen:

Dr Nelson: Well, I don't always do it, but sometimes you'll be talking about some sort of subject and I'll often slow down or kind of gauge the class's response... those who are listening, hopefully many of them are. If you get a lot of puzzled looks, there's always a few people in the class who you can guarantee that are, one, listening, and, two, giving you a lot of visual feedback, and if you start getting those looks that they have no idea what you're talking about, then usually, at that point, I try to... I sort of deviate from the scientific explanation.

Dr Owen: Some of the best [analogies] come up totally spontaneously when a student asks a question and they're not understanding the concept. I'll come up with an analogy on the spur of the moment, and, often I'll say, 'what a great analogy.' Then, of course, I don't write them down, and now I don't remember them, so that's that creative aspect of teaching we talked about. It's much more fun if they come up that way.

Although instructors perceive that most analogies are developed spontaneously, there are some analogies they develop intentionally to address difficult topics, particularly if other methods of explanation are not working.

Dr Horn: Sometimes, you [use analogies] very deliberately. I mean, I have some that I said, 'well, gee, this is a real struggle area. What is like this?'; and you actually, physically just sit down and think and go, 'what is similar to this that they would be more comfortable with?' I can think of examples like that, too, where I just... it wasn't a matter of just popping into your head, but it was actually a tried to rationally come up with it.

Whether the analogies were developed spontaneously or deliberately, the instructors perceived that they only developed analogies for topics the students find difficult to understand—and only as a supplement to a chemical explanation for those topics.

Dr Horn: I tend to use them after the theoretical explanation of the chemistry, from the chemistry angle. [...] That's the only piece of advice I can give is to [use analogies] after you've talked about the chemistry and why the chemistry's important. [...] Once you've given them something, you know, that's confused them a little bit, then they'll understand, and they'll be paying more attention to you 'cause if you explain 'this is a way to help you understand it,' they'll listen up to that a little better.

Overall, analogies seem to be a very personalized teaching strategy for the instructors who participated in the current study. When we asked them where the analogies they use in

class came from, they mentioned that they developed most of them, whether spontaneously or deliberately. In rare cases the instructors mentioned using an analogy from a colleague or from a textbook. Often, the instructors modified any pre-developed analogies to make them their own before sharing them with their students.

Assertion 5

Biochemistry instructors' perceptions of how they present analogies in class—and of how analogies should be presented in class—correlates well with what is known in the literature to support student learning from and with analogies. However, their classroom use of analogies does not always coordinate with how they perceive analogies should be used.

The analogy literature shows that there is often a lack of spontaneous transfer between analog and target concepts. Anolli *et al.* (2001) suggested that this lack of transfer occurs because students are not aware of the connection between analog and target concepts. Just teaching the analogy is not sufficient to promote transfer. Neither is drawing attention to the analogy. Instead, it is necessary for students to recognize the connection between the attributes of the analog and target concepts.

There are several steps that can be taken to help students recognize the connection between analog and target concepts. One step is to teach students how to use analogies and to help them recognize the role that analogies can play in learning (Klauer, 1989; Goswami, 1993; Venville *et al.*, 1994; Harrison and Treagust, 2000). Another is to explicitly state the similarities between the analog and target concepts and the limitations of the analogy (Harrison and Treagust, 1996). Analogies are often used to make new information intelligible by drawing comparisons to information the students already know. If teachers explicitly identify the similarities and differences between analog and target concepts, students should be less likely to incorrectly apply the attributes of the analog to the target.

The biochemistry instructors we interviewed seemed very aware of the ways that analogies *should* be presented in class, and the majority of these ways correlate well with research-based strategies that are known to promote analogical transfer. Interestingly, though, how biochemistry instructors say they *should* present analogies in class does not always coordinate with how they *do* present analogies in class.

Biochemistry instructors perceive that they point out the limitations of the analogies they use in class, more often than they do. Most of the instructors we interviewed indicated that analogies have limitations that should be mentioned to students. For example, Dr Allen thought it was important to identify how far her students could take a particular analogy.

Dr Allen: As a teacher, you have to make clear that, 'OK... this is as far as this analogy goes, and it stops here 'cause you can't extend it beyond this point' 'cause it is just an analogy, and it's not a true representation of the system.

Given the importance that the instructors placed on explicitly stating the limitations of the analogies they used, we expected to see this behavior demonstrated in the classroom. However, out of

the 110 analogies we observed in five different classes, only five limitations were mentioned, and three of these limitations referred to the limitations of the lock and key analogy for enzyme–substrate interaction (that enzymes and substrates are not rigid like a lock and a key).

Biochemistry instructors perceive that they explicitly map analog concepts to target concepts when presenting an analogy.

Consistent with what is known in the literature, biochemistry instructors in the current study said that it is important to make explicit connections between analog and target concepts when presenting an analogy.

Interviewer: What do you think instructors in general could do so that the students would learn better with the analogies? [...]

Dr Castle: Make sure that there is that link between... or make sure that there's not a disconnect between what the analogy was and what the concept was.

Interviewer: Meaning that you actually...?

Dr Castle: That you actually try to bridge that explanation of what that means relative to the concept.

In the biochemistry classes we observed, three quarters of the analogies were explained to some extent, although very few were explained in great detail.

Biochemistry instructors perceive that they use figures or models to supplement their presentation of an analogy more often than they do. Almost every biochemistry instructor we spoke with mentioned using pictures or models to supplement their presentation of an analogy. In fact, many instructors would pull out those pictures or models as we talked to them about specific analogies to from their classes. However, as previously mentioned, most (85%) of the analogies we observed in biochemistry classrooms were presented without an accompanying picture. When biochemistry instructors did include a visual representation of either the analogy or the analog concept, that representation came in the form of either two-dimensional pictures/photographs or three-dimensional objects.

Summary. Overall, it appears that biochemistry instructors have a good intuitive understanding of how analogies should be presented in order to promote analogical transfer. However, in the middle of the messy, real world of classroom teaching, their understanding was not always implemented. Our observations and our conversations with the instructors indicated that they were not always aware of when they were using analogies in their classrooms and, as a consequence, may not have presented them as they knew they should.

Conclusions

All of the instructors interviewed in the current study used analogies to help their students develop understandings of biochemical concepts. Based on comments from a previous study (Orgill and Bodner, 2007), we know that the majority of biochemistry students appreciated their instructors' use of analogies and believed they were better able to understand biochemical concepts when they learned through the use of analogies

None of these biochemistry instructors had any formal training in the use of analogies, but their classroom teaching experience led them to develop personal philosophies about how analogies should be presented in class to promote student learning. Specifically, they said that the similarities and differences between analog and target concepts should be pointed out to students and that figures or models should be used to supplement analogy presentation. Although the teachers have developed these personal philosophies that are consistent with practices known to support analogical transfer (Beveridge and Parkins, 1987; Harrison and Treagust, 1996), they applied these practices inconsistently. For these instructors, analogies are such a natural way of communicating that they are not always aware of when they are using analogies and, consequently, do not present or use analogies as effectively as they could.

As one example, all of the instructors in this study said that it is important to point out the limitations of an analogy. However, in the classes we observed, limitations were only rarely mentioned explicitly. This puts students at a disadvantage. Harrison and Treagust (1994, 1996) and Holton (1984) have noted that students seldom understand enough about a target concept or an analogy to be able to identify the limitations of an analogy. As such, instructors must make these limitations explicit to their students.

Jarman (1996) indicated that beginning teachers and student teachers do not always recognize the limitations of the analogies they use. The instructors in this study, however, were not beginning teachers. Each of them had extensive experience in both the field of biochemistry and as an instructor of biochemistry classes. It is more likely that these teachers believed the limitations of the analogies they used were self-evident, as has been expressed by instructors in other studies (Thiele and Treagust, 1994a). Interviews with biochemistry students (Orgill and Bodner, 2007) indicate that this assumption is not valid, as students are not always aware of the limitations of the analogies used in their biochemistry courses.

Overall, the instructors we interviewed do not seem as aware of or worried about some of the potential challenges associated with analogy use. Instructors also seem unaware of the fact that the process of creating and evaluating analogies can support students' development of biochemical knowledge. The instructors we interviewed provided all of the analogies used in their courses; they did not ask students to participate in the analogy creation process. Research indicates, however, that there are several potential advantages of having students generate and evaluate their own analogies for a concept. First, the process of generating an analogy may help students construct and organize their own knowledge about a topic. It may also be a tool by which students become responsible for their own learning. Second, the process of evaluating and modifying analogies can cause students to: (1) change their explanations of phenomena; (2) view a concept from a new perspective (Middleton, 1991); (3) ask stimulating questions about their understanding of a phenomenon, which highlights aspects of the phenomenon students don't understand; (4) focus their thinking on a particular aspect of a phenomenon; and (5) discover

new (not problem-related) problems with their understanding of scientific phenomena (Wong, 1993a, 1993b).

Based on our interviews, we believe that biochemistry instructors use analogies naturally in their teaching and with the best of intentions. That they are less aware of some of the potential challenges associated with analogies and uses of analogies to promote knowledge development is not surprising, as they, like most tertiary science instructors, have little training in pedagogy or learning theory—a fact they referred to often in our interviews. Interestingly, because these instructors believed that analogies promote learning and because they recognized that good analogies are hard to develop, many of them expressed a desire to have access to more analogies that they could use in their classrooms. This desire could be turned into a professional development workshop. In the workshop environment, biochemistry instructors could come together to analyze the quality of existing analogies, be introduced to the factors that have been shown in the science education literature to promote analogical transfer (see Orgill and Bodner, 2004), and work together to improve the quality of analogies they are currently using in their classrooms. Those analogies could, then, be shared among the group. The end result of the workshop would ideally be a bank of quality biochemistry analogies, as well as instructors with increased knowledge and awareness of ways to promote analogical thinking in their classrooms.

Overall, this study is only one step toward exploring the use of analogies in biochemistry courses and biochemistry students' analogical reasoning abilities. Future research should examine students' interpretations of specific biochemistry analogies and the ways those analogies promote or inhibit deep understanding of biochemical concepts. Given that analogies become part of students' prior knowledge and can, thus, influence their interpretation of external representations, future research should also examine the influence of analogies on students' biochemical visual literacy. Finally, because the ultimate goal of using analogies in an instructional setting is to support students' learning, a logical next step in this field would be to test different classroom interventions in order to determine the specific conditions for analogy instruction that support student learning in biochemistry, as well to determine which types of biochemistry students benefit the most from analogy instruction. There remains much to be done to examine biochemistry students' analogical reasoning skills and the conditions that support the development of this essential cognitive skill (Anderson and Schönborn, 2008; Schönborn and Anderson, 2008).

Appendix A: instructor interview guide

(1) Background questions

- Can you tell me a little about your biochemistry background?
 - In what subjects do you have your degrees?
 - Where did you receive your degrees?
 - What kind of biochemistry classes did you take during your studies?

■ What kind of research do you do, briefly?

■ Did you teach or TA biochemistry courses during your studies? What can you tell me about that experience?

■ What made you decide to teach biochemistry courses?

(2) Teaching style questions

- What biochemistry classes do you teach?
- How long have you taught these classes?
- Describe your teaching style in the biochemistry classes. (Do you think you have a different teaching style when you teach other classes? If so, why do you think it varies?)

• What experiences (either good or bad) have influenced the teaching style that you have developed?

• What do you think is the most important characteristic of a good biochemistry teacher? (Think back to your own experiences as a teacher and as a student.)

• What do you think are the difficulties that students face when learning biochemistry?

• I'm interested in the use of analogies as a teaching technique. An example of an analogy is "an atom is like a bookcase." The word "analogy" has different meanings to different people. Can you describe for me, in your own words, what an analogy is to you?

• In what ways do you think that analogies are useful for teaching and learning science?

• Do you use analogies in your teaching? What kind? How often? Under what circumstances?

• What do you think are the reasons that you do/don't use analogies in your teaching?

• Where do you get the ideas for the analogies you use in class?

• Are there specific ways that you use analogies in your class? (Are there special circumstances under which you use them? Are there certain students with whom you use them? Do you introduce them in a certain way?)

• What do you expect your students to do with the analogies you use in class? What do you think the students really do with the analogies you use in class?

• How do you prepare the analogies you use in class?

• If you were to compare the use of analogies with other teaching methods, what are the advantages and disadvantages of teaching with analogies?

• How do you feel about the analogies that are used in the textbook you use in your class? Do you think these textbook analogies are useful to you? To your students?

(3) Analogy questions

• How can analogies benefit students?

• What difficulties could students encounter with analogies?

• What kind of students will benefit from analogies? Why?

• What are some of your favorite biochemistry analogies (that you use and/or have heard used)?

• What does _____*** analogy mean to you? (What kind of information does it convey to you? Do you see any benefits/difficulties associated with using this analogy?)

• Are there certain subjects/topics that should/should not be taught with analogies?

- Can you give me an example of a really good analogy? What makes it a good analogy?
- Can you think of any analogies that you have heard being used in biochemistry classes that aren't so good? What are the problems with these analogies?
- How do you think students use analogies? Do you think they know how to use analogies?
- What do you think could be done to help students use analogies more effectively?

*** The particular analogy used in each interview varied from participant to participant. Generally, we chose analogies that were presented in the classes we observed.

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