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Articles

Locks and Keys

AN ANALYSIS OF BIOCHEMISTRY STUDENTS' USE OF ANALOGIES

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Analogies can be powerful teaching tools because they can make abstract material intelligible to students by comparing it to material with which the students are already familiar. In this study, we interviewed 43 students to determine the specific ways they use analogies to learn and function in their biochemistry classes. We found that students use analogies in a variety of unique ways to promote understanding, visualization, recall, and motivation in their biochemistry clases. However, their uses of analogies did not always correlate well with their instructors' purposes for using analogies. We also discuss the teaching implications of these findings.

Keywords: contributions from cognitive science and educational psychology to student learning, teaching and learning techniques, methods and approaches, tertiary-specific education, student conceptual and reasoning difficulties.

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. Analogies can make the connection between these abstract concepts and more concrete concepts with which students are already familiar. 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 actually interfere with students' learning of class material [1, 2].

Analogies are comparisons between two domains—a familiar domain often known as the "analog" and a less familiar domain known as the "target." Analogies are used by both instructors and students in science classes. Whereas a significant amount of research has been reported about the way teachers and textbooks use analogies to teach science, less research has been done on how science students use analogies to learn.

In studies with high-school students, various authors [3–6] found that the use of analogies in a science classroom may aid students' understanding of unfamiliar concepts and that, at times, analogies may contribute to conceptual change. They also found, however, that students do not always use analogies spontaneously to understand a new concept or solve a new problem, even when they understand the analogy [3, 5]. Instead, some students use the analogy as an algorithm for problem solving without understanding the analogy or the target concept being taught with the analogy [5].

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There have been relatively few studies about how college science students use analogies, and the studies report mixed results. Friedel, Gabel and Samuel [7], for example, found that there was no increase in chemistry problem-solving performance when analogies were used to teach stoichiometry problems. Clement [8, 9], however, found that students spontaneously generate analogies to solve physics problems in an experimental setting.

To date, no research has reported how college-level biochemistry students use analogies to learn; and, yet, biochemistry classes and biochemistry textbooks are full of analogies [10, 11]. Additionally, previous work has shown that a majority of biochemistry students like, pay attention to, and use analogies to learn in their biochemistry classes [2, 10]. Simple examples of biochemistry analogies can be found in the use of the term "chaperone" to describe certain proteins and the tendency to describe cell membranes as "fluid mosaics." Several concepts in biochemistry classes are almost exclusively explained with reference to an analogy. For example, the interaction between substrate and enzyme is often compared to a lock and a key. ATP is referred to as cellular "currency."

Given the presence of analogies in biochemistry teaching and learning, we felt that it was important to understand how biochemistry students perceive the analogies used in their classes so we, as instructors, can use analogies more effectively in class. This paper examines results obtained as part of a larger study in which the following guiding research question was used: "What are biochemistry students' perceptions of analogies and their use in biochemistry classes?" Here, we focus on the subquestion: "How and when do students use analogies to learn in their biochemistry classes?"

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METHODOLOGY

Data Collection

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. Because we wanted to discover the range of experiences that all biochemistry students have with analogies [12], we asked students from many different biochemistry classes to participate in the study. We asked for volunteers from two introductory biochemistry classes—a 100-level class for freshman biochemistry majors that had no prerequisites and a 300-level survey biochemistry class designed for majors in the School of Agriculture for which one semester of organic chemistry was a prerequisite—and one upper-level biotechnology class that had a biochemistry prerequisite. We also obtained volunteers from a population of advanced undergraduate and graduate students who were taking classes with a biochemistry prerequisite. 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.

The individual interviews were semi-structured and conversational, each lasting 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: whether 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. The interview guide can be found in Appendix A. We continued to interview students from a wide range of biochemical backgrounds until successive interviews no longer revealed new ways of experiencing analogies in biochemistry classes, a phenomenon known in qualitative research as "saturation" [13].

Theoretical Framework

Qualitative research such as this must be based on a theoretical framework or perspective [14, 15]. The role of the theoretical framework might best be illustrated with an analogy. In a typical experiment performed by a practicing biochemist, the researcher chooses a particular analytical instrument to study a particular aspect of the material in which he or she is interested. The choice of instrument obviously affects the type of data the researcher will obtain and later analyze and interpret. One would not expect to obtain mass data from an HPLC, for example; nor would one expect to obtain retention time information from a mass spectrometer.

For qualitative research studies, the theoretical framework plays a role analogous to the role of the instrument in a biochemistry experiment. A theoretical framework is a system of ideas, aims, goals, theories and assumptions about knowledge, about how research should be carried out, and about how research should be reported. The framework influences what kind of qualitative experiments can be carried out and the type of data that result from these experiments [16]. Because a theoretical framework has great influence on the design, data collection, and data analysis of qualitative studies, qualitative researchers must make explicit the framework chosen for a particular study. The theoretical framework we chose to guide this research is phenomenography [17].

Phenomenography is an empirical research tradition that was designed to answer questions about thinking and learning, especially in the context of educational research [18]. Phenomenographers seek to identify the multiple conceptions or meanings that a group of people have for a particular phenomenon and to describe those conceptions from the people's points of view. The focus of a phenomenographic study is not on providing rich descriptions of how individuals experience a given phenomenon or on quantifying the number of individuals that experience a phenomenon in a given way. Rather, it is on describing the variation in experiences across a group [12, 19, 20]. As such, detailed descriptions of the backgrounds of individuals in the group are not typically included in phenomenographical studies.

Marton [21, 22] believes that there are a limited number of qualitatively different ways in which different people experience a certain phenomenon. From this theoretical stance, it is irrelevant whether those conceptions are considered "correct," "incorrect," "useful," or "not useful" by current standards. The aim is simply to elucidate the different possible conceptions that people have for a given phenomenon. In phenomenography, these conceptions are termed "categories of description."

There are certain benefits to using the results of phenomenographic research in a higher education institution. At this level of instruction, students are generally encouraged to develop conceptual understandings [23]. It is often the goal of teachers to help their students develop conceptions that are consistent with those held by recognized experts in various fields. However, students often have multiple different conceptions of a phenomenon that are not necessarily consistent with the conceptions held by experts. Marton [18] claims that "a careful account of the different ways people think about phenomena may help uncover conditions that facilitate the transition from one way of thinking to a qualitatively 'better' perception of reality" (p. 33). Thus, information about the different conceptions that students hold for a particular phenomenon may be useful to teachers who are developing ways of helping their students understand a phenomenon from a perspective that is consistent with the scientific community [24].

Data Analysis

We began our data analysis by transcribing each of the interviews verbatim. The interview transcripts became the data that we analyzed to determine biochemistry students' conceptions of the analogies used in their classes, specifically how and when they use these analogies to learn. We read through the transcripts several times, looking both for similarities and differences within them. In this process, we developed initial categories that described different ways students use analogies or different circumstances in which students use analogies. In phenomenography, the only ground rules for category development are internal consistency and parsimony, or finding the minimum number of categories which explain all the variations in the data [17].

With these initial categories in mind, we reexamined the interview transcripts to determine whether our categories were sufficiently descriptive and indicative of the data. This second review of the data resulted in modification, addition, and deletion of the category descriptions. We continued this process of modification and data review until the modified categories seemed to be consistent with the interview data.

Once the categories of description were consistent with the transcript data, we used a data management program to assign portions of the transcripts to their corresponding category descriptions. The categories of description will be discussed individually in the following Results and Discussion section.

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.

TABLE I
Categories of analogy use

Categories of analogy use	Specific uses of analogies
To Understand Information from Class	1. To develop an initial understanding of a concept during a class 2. To build on existing incomplete knowledge about a target concept 3. To check their understanding of an instructor's explanation 4. To organize their thoughts about a concept
To Visualize Abstract Concepts	1. To develop a picture of abstract biochemical substances or processes or to visualize the relative sizes of biochemical substances
To Remember or Recall Information	1. To connect to information in their memories when they get stuck on exam questions (as a memory trigger)
As Motivation	1. As a break from the "monotony" of lecture to rest their minds, "catch up" and "reflect" on notes, or to refocus their attention on course material 2. As a way of determining that their instructors are interested in the students' success
To Communicate	1. To communicate with each other during study groups 2. To communicate what they have been learning in class with their family and friends
To Determine What Information Is Important	1. To determine which information instructors will put on exams
To Determine the Meanings of Words in English	1. To determine the meanings of English language words

RESULTS AND DISCUSSION

Most of the ways students use analogies could have been anticipated because they correlate strongly with the benefits of using analogies identified in prior research [2]. In general, students use analogies to understand, to visualize, and to remember course information. However, the specific ways in which students used analogies in their biochemistry classes were both surprising and innovative. The categories of analogy use reported by the students and the specific ways of using analogies are listed in Table I and discussed in the following sections. When quotations from student interviews are used to support the category descriptions, the symbol "I" is used to refer to the "Interviewer."

Students Use Analogies to Understand Information From Class

The primary way in which biochemistry students reported using analogies was to understand information from class. In another study [10], biochemistry professors expressed a concern that students would rely solely on an analogy to understand a concept and never develop a complete understanding of the concept. Similar concerns are expressed in the literature [25, 26], but the students interviewed in this study noted that, to understand a concept well, they have to study more than the analogy. Instead, they used the analogies their teachers provided in different ways: to gain an initial understanding of a concept, to build on incomplete understandings, to check their understandings of instructors' explanations, or to organize their thoughts about a concept.

To Form an Initial Understanding of Concepts—Analogies are most often used in an educational setting to help students understand new information in terms of already familiar information and to help them relate that new information to their already existing knowledge structure [26–30]. Ausubel (quoted in Bodner, [31]) states, "to learn meaningfully, individuals must choose to relate new knowledge to relevant concepts and propositions they already know" (p. 877). When knowledge is constructed in a meaningful manner, learning tends to be relevant, applicable, and memorable for students, more so than learning by rote.

In trying to understand biochemical information, students use analogies as a stepping-stone, a way to develop an initial understanding of a concept. For example, the instructor of the 100-level class compared the cooperative binding of oxygen gas to hemoglobin to tearing a stamp out of a 2 $\times$ 2 pane of four stamps. To remove the first stamp, two perforations must be torn; successive stamps are easier to remove because fewer perforations must be torn, just as the binding of each successive oxygen molecule to hemoglobin requires less energy than that of the previous molecule. Students used this analogy to develop an initial, basic understanding of the binding of oxygen to hemoglobin.

According to the students, the analogies that are used in this way are useful at the moment they are presented, when students are trying to comprehend what an instructor is saying in class, but they are not always useful when students are studying. This is particularly true of students who feel they have a good grasp of content knowledge.

> Shawna: I did not remember the specific analogies used [in my biochemistry class], but when hearing them again, they are good ways to explain the material and did help me feel that I understood the material, so much that I forgot the analogy and just remember the take home on the structural attributes.

Biochemistry students at all levels mentioned using analogies to develop an initial understanding of a concept. However, once they had developed a comfortable understanding of the concept, many students stopped using the analogy to think about that concept. Students only referred to the analogy if they became confused about the target concept. Advanced students, who have a more developed understanding of biochemistry concepts than undergraduate students, forgot ever using an analogy to develop an

initial understanding of the target concept unless we asked them if they remembered hearing a specific analogy, to which they responded, "Oh, yeah. I forgot about that. I remember that it helped at the time, but I have not thought about it for a long time." This is promising news for instructors who are concerned that their students will rely on analogies and not learn the "real" concepts.

> Nathan: I think that there are a lot of difficult concepts that [. . .] can only be learned through analogies. Once the connection is made as to what that means, it's fine. You don't need to use the analogy; but especially beginning and even with difficult concepts, I think that analogies are pretty much the only way to really communicate the idea.

To Build on Existing Incomplete Knowledge—Analogies can also help students view a concept from a new perspective. Gick and Holyoak [32] noted the following about the ability of an analogy to alter our perceptions:

> To make the novel seem familiar by relating it to prior knowledge, to make the familiar seem strange by viewing it from a new perspective—these are fundamental aspects of human intelligence that depend on the ability to reason by analogy. (p. 2)

A few students we interviewed used analogies to complete their understanding of a biochemical concept. For example, Brent said that he had heard of the concept of "induced fit" before taking his biochemistry class. He could explain the concept in words, but he did not feel that he had internalized or understood the concept until his instructor presented an analogy in which the induced-fit model of enzyme/substrate complementarity was compared to putting a hand in a plastic glove, during which process the shape of the glove conforms to the shape of the hand. Brent told us what he thought about that analogy.

> Brent: I think that was the first time I really ever understood induced fit. I love that analogy. That made great sense to me. I don't know how to say that, but it makes total sense. [. . .] With a binding site, you always think it has to be just the right formation for something, but with the glove, the glove's not the same shape as your hand. I mean, it correlated very well, so I mean, it did help. Definitely.

The analogy helped Brent view the concept of induced fit from a different perspective, and that perspective made the concept of induced fit intelligible and plausible to him [33].

It is worth noting that none of the students interviewed in this study mentioned using analogies to overcome *incorrect* understandings of a target concept. By their reports, the students only use analogies to build on nonexistent or incomplete understandings. However, there are many reports in the literature of teachers using analogies to overcome students' misconceptions [3, 6, 34–40]. Because students do not recognize this potentially important role of analogies, instructors must be very explicit with their students about their purposes when they are using analogies to help their students overcome incorrect biochemical ideas.

To Check Their Understanding of Instructors' Explanations—Although the literature is replete with examples of how students can increase their understanding of target concepts through analogies (teacher-provided or student-generated), one of the students whom we interviewed used analogies as a complement to her learning. She said that she made up analogies during class to check if she understood her instructor's explanations for different biochemical concepts.

> Laura: I know every once in a while, I'm sitting in a class, and a professor's struggling, trying to explain a concept, and I have my own little analogy for it in my head that makes it make sense to me, and sometimes, if I'm in a comfortable environment, I'll say, "is it kind of like . . ." and give my analogy 'cause I think that that helps other students.

We asked Laura if she found using analogies to be an effective way to check her understanding of concepts presented in class. She said the analogies gave her a way to discuss what she understood about the concept with her instructor or peers.

> Laura: Sometimes I'll say, "is it like this?" and someone will say, "oh, no! It's nothing like that." Then I didn't get it well in the first place.

Although this use of analogies has not previously been reported in the literature, we believe that it requires special consideration from biochemistry instructors. Lemke [41] argued that students are often more comfortable with the familiar language of an analogy than they are with more technical, "scientific" language. In order to determine if students understand scientific explanations, teachers might ask their students to work in small groups to develop simple analogies for biochemical concepts. The benefits of this process would be threefold: first, developing the analogy allows students to begin to think meaningfully about the concepts [42, 43]; second, the student-generated analogies allow instructors to formatively assess their students' current understandings of the concepts so they can adapt instruction to meet the students' needs [44]; and third, if the analogies are shared with the class, each different analogy will allow the students to look at the concept from a different perspective, which can contribute to the development of a deep understanding of the concept [45].

To Organize Their Thoughts About a Concept—Finally, students use analogies to organize their thoughts about a concept so they can better understand that concept. Thiele and Treagust [30] argued 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 [29] or to particular differences between the analog and target domains [46]. Most biochemical concepts are multi-faceted, and true understanding occurs when students are able to understand and integrate all the component parts of a concept. Michael, a graduate student who makes up his own analogies while he reads journal articles, uses analogies in this way.

> I: So how does the analogy help you [. . .]?
> Michael: Because sometimes, analogies simplify a difficult subject, you know. If it's so difficult, so confusing, or so complex, if you can use analogy, you can break it down into small, small chunks and then you can assemble everything together again. I think it helps. So, it helps simplify difficult or complex subjects, especially in biochemistry where things can be really complex.

It should be noted that the graduate students were the only students to use analogies in this way. The undergraduate students did not use analogies to make connections between different scientific concepts. Once again, if biochemistry instructors are using analogies to make connections between scientific concepts, they will have to make that purpose clear to their students, particularly if the students are undergraduates. The students do not recognize this role of analogies.

Students Use Analogies to Visualize Biochemical Concepts

Almost every student with whom we spoke said that their ability to understand biochemical concepts was aided by their being able to visualize the different biochemical structures and processes. The students in this study and previous studies [26, 29, 47–49] report that analogies help them visualize abstract concepts or unobservable phenomena. For example, one instructor used an analogy for competitive inhibition in his class. He talked to the students about playing the game "musical chairs." If, when the music ends, there is someone (an inhibitor) in the seat (the active site) already, you (the substrate) cannot sit in the seat. Many of the students found this analogy to be especially helpful. Tonya said, "[The analogy] gives me a picture in my mind of what exactly it is he's talking about." Analogies may provide a concrete reference that students can use when thinking about challenging, abstract information [29, 35].

Students in the current study also mentioned using analogies to develop insights about the relative strengths of intermolecular forces or the relative sizes of biochemical entities. Instructors often use the words "large" and "small" in their classrooms, but what do those words mean when referring to things that are so small you can't see them? Students have no internal calibration for these terms. For example, students know that hydrogen bonds are weak bonds, but, at the same time, the two strands of DNA that are held together by hydrogen bonds are very stable. How can a weak bond be used to hold two strands together? One of the instructors used an analogy to explain the additive strength of hydrogen bonds when he compared them to Velcro. Brad said that this analogy helped him.

> Brad: Well, I mean, [the Velcro analogy] pretty much explained it to me [. . .] until you have some concept of what it means, like, strong and weak, [. . .] molecules bonding didn't really have any meaning to me. You know, what's strong? What's weak? What scale are you talking about?

Although Brad did not specifically mention the use of visual aids in connection with using analogies to visualize the relative sizes of different biochemical substances, other biochemistry students have mentioned that they feel like they have a better understanding of what their teachers meant them to understand when the teachers use visual aids in conjunction with their analogies than when they use analogies alone [2]. We believe that analogies with visual aids can also help students visualize relative sizes, whether the visual aid be of the analog concept or an aid comparing the analog and target concepts.

Students Use Analogies to Remember or Recall Information

Students use analogies to remember information from their courses. The students provided several reasons why analogies are easier to remember than straight biochemical explanations. First, analogies relate unfamiliar biochemical concepts to familiar experiences. Second, analog concepts are different enough from the normal course of classroom discussions that they become memorable. Third, analogies can act as memory triggers when students are trying to recall information from class for an exam.

While there were some students who intentionally studied analogies in preparation for an exam, the majority of students in this study used analogies in a more indirect manner. Apparently, analogies are memorable enough during their initial presentation in class that they act as memory triggers when students get stuck and cannot remember a more direct way to answer exam questions. The memory of the analogy connects them to the information they need. One of the graduate students remembered an analogy comparing Route 66 to a linkage map while he took an exam in a biotechnology class. He said that the analogy helped him focus on important features of the linkage map as he answered questions on the exam.

Venville and Treagust [6] reported that analogies can play specific roles in memory recall. Although biochemistry *professors* did not give much value to the role of analogies in memory recall [10], biochemistry *students* found memory recall to be an important use of analogies.

> Steve: It triggers something in your head. If you have . . . if you have something that's hard to understand attached to something that, you know, you might use in your everyday life, just something . . . something might trigger you, you know, in your head, in your test. It's easier to remember stuff you deal with everyday than it is hard stuff, so if you can remember the everyday thing and then remember that the biochemistry is attached to it, you're just going to remember it a lot easier.

Students Use Analogies as Motivation

Analogies can play a motivational role in meaningful learning [47, 49–51], and biochemistry students seem to recognize this fact. Previous research [33, 52] has shown that students' motivation can be linked to their level of engagement in a task and their willingness to persist at a task. If students are not motivated to learn subject matter, it is quite probable that they will not invest the time

and energy needed to learn the subject matter or to affect conceptual change. However, the more students are motivated to interact with subject matter, the more likely they are to process information meaningfully, which can result in conceptual change.

The students in this study report that they are likely to pay attention to an analogy from class because the analogy is something different from what is normally happening in the classroom. They use analogies as a needed break from scientific talk; as a time to refocus their attention; and, interestingly, as a method of determining whether their instructor is concerned about their success in the class.

As a Break in Lecture—Students who feel motivated to learn say they are interested in course material and tend to pay attention to what is happening in class. Analogies provide a break from the "monotony of lecture." They give students a period of time in which they catch up on the notes they are taking, think briefly about what they have been hearing in class, or simply let their minds rest from the technical language to which they have been listening. This is true for both beginning level students, like Stephanie who says that class can get boring, and advanced students, like Brian who says he has problems paying attention during the entire class period.

> Stephanie: [The analogy] relieved the boredom of the class, but at least ... seriously, if you sit in class and he was just talking the whole hour, it gets boring, so anything to break that up. [...] It helps you pay attention a little bit more, I guess. "Oh ... what wacky thing is he doing now?" So you pay attention to it.

> Brian: When you sit through [class] and someone gives you an analogy then explains what they mean by it ... I think analogies are great, actually. I've learned a lot of different concepts that maybe I wouldn't have learned from an instructor based on my ADD problem that, because of an analogy, you know, you sit there and you listen. You think, "well, this guy's talking about something else besides what I need to know. I'm going to sit here and listen." You know?
> I: So you pay attention to it.
> Brian: Yeah. You pay attention because you want to know what he's getting at. You know, you think, "well, what is he talking about?" so you listen to the analogy, and you realize what he's comparing to and what he's trying to get you to know, and you're, like ... then you leave class saying, "man! I learned something today!" So, yeah. Analogies are good.

Lemke [41] has asserted that students are three to four times more likely to pay attention when language is familiar. Dagher [47] says that the language of analogies can demystify scientific language and reports that the use of narrative analogies tends to result in higher student motivation and engagement. Part of the motivational role of analogies is also thought to be due to the way in which analogies relate class information to the students' real-world experiences [49]. As students pay attention to and relate new information to their experiences, they will be motivated to learn the new information meaningfully.

To Determine Their Instructors' Interest in the Students' Success—Several students in this study mentioned that they are more motivated to learn when they believe that their instructors are interested in their success in the class than when they feel that the instructor is only in the classroom "because it's his/her job." Surprisingly, many students stated that an instructor's use of analogies is one of the factors they take into account to determine whether their instructors are concerned about the students' success. They expressed a belief that an instructor's use of analogies shows that the instructor has taken time to prepare his or her notes for class because they are concerned about the students' success in the class. The students also believe that instructors use analogies because they are trying to make learning easier for their students by reflecting on their own difficulties in learning biochemistry.

> I: So you do like it when teachers use [analogies]?
> Amanda: Right. Which also shows that they're putting effort into preparing the notes. It's not just the notes that they used last year or ... you know, they're actually putting effort. They've thought about, "how would I like to learn this," and then that's how they teach it.

This last motivational role of analogies is not a main focus in the literature on analogies, but it may be important for biochemistry instructors to know that students are motivated to learn when they feel that their instructors are concerned about their success. While this concern can be demonstrated in multiple ways, students see the use of analogies as evidence of an instructor's concern for his or her students.

Students Use Analogies to Communicate

At times, an analogy can also provide familiar language with which students can express their understanding of a target concept [41, 47]. It is possible that students understand target concepts but do not have mastery of the scientific language and grammar necessary to explain what they know. Analogies can provide a familiar language with which to communicate their understanding, and biochemistry students mentioned using analogies to communicate in two specific ways: to communicate with their classmates while they are studying and to communicate what they are learning in biochemistry class to their friends and family.

To Communicate With Each Other as They Study—Students use analogies to communicate with each other as they study. Beth mentioned that when she and her friends meet to study for exams, they quiz each other over the course material. Sometimes, when one of the group members says that he cannot remember a particular concept, another group member will remind him of the concept by bringing up an analogy that was used in class. The group then uses the analogy as a foundation for studying the concept and for constructing useful knowledge about the concept. When asked, "How do you use analogies when studying?" Beth remembered some specific analogies used in her course, including

one in which DNA was compared to a recipe book, and said that she and her peers use them while studying:

> Beth: Well, when we're talking about the situation and stuff like that, we'll say, "OK. This is where he took the string or this is where . . . this is the recipe," like we're studying for the quiz now. "This was the recipe [analogy]. OK." So, we'll talk about what was done, what was basically done, and, "OK. How does that actually work?" 'cause that's very useful if you don't actually understand what it does, so . . . and I think that's also very well incorporated into the class. It's not just a goofy analogy, not just a goofy example in class. It is explained . . . how does this relate specifically to what we're talking about? What does each component represent, not just, "this is an analogy, laugh at it."

To Communicate What They Are Learning to Family and Friends—Students also use analogies to communicate what they have been learning in their classes with their friends and family. These acquaintances are interested in what the students are learning in class, but students do not believe, in most cases, that their acquaintances have enough technical knowledge to understand a direct explanation of biochemical concepts. They do, however, have enough background to understand an analogy of a biochemical concept. Several students commented that they use both analogies their instructors provide and analogies they make up on their own to share what they have learned in class with their family and friends. Amy, a student in the 100-level biochemistry class, says she really enjoys making up analogies to explain scientific concepts to her little brother and sister.

> I: Do you like coming up with analogies?
> Amy: Yeah. Yes I do.
> I: Why do you think that?
> Amy: Um. Because a lot of times, I have to explain things to people. Um, when you've done that at all, scientific or understanding . . . where I'm coming from, they just don't have the kind of education, especially with, like, my little cousin and my little brother and sister.

Students Use Analogies to Determine When to Pay Attention

The information presented during a biochemistry course can be overwhelming to students who are unfamiliar with the subject, so part of a student's challenge in a biochemistry class is to determine which information is the most important to learn. Knowing which information is most important to the professor has a practical application: that information is likely to show up on an exam. Several students in this study mentioned using analogies to determine what information is important in class.

> Susan: If [instructors] stop and make a big deal about [an analogy] 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.

As previously mentioned, students tend to pay attention to analogies because of their familiar language and their novelty in science class. Because students equate instructors' use of analogies with the importance of a particular concept, biochemistry instructors may want to consider selectively using analogies for difficult or abstract concepts that they want their students to particularly remember instead of using analogies to describe any difficult or abstract concept.

Students Use Analogies to Determine the Meanings of Words in English

Analogies can create specific problems for students who are second-language learners. Not only must they correlate concepts between the analog and the target, but they must translate the meanings of the words describing the analog and the target into their first language so they can begin to understand the analogy. For these reasons, understanding analogies can be very taxing on second-language learners. The second-language learners whom we interviewed said that they typically rely on their instructors' direct explanations to understand biochemical concepts instead of on their analogies. One exception to this was analogies which were accompanied by visual aids, which could be understood with less cognitive effort than verbal analogies.

The words used to describe analogies may also be confusing for second-language learners. One of the students with whom we spoke was an international graduate student for whom English was a second language. She came to the United States with little training in English and had been in the country for approximately a year when we interviewed her. We asked her to explain her understanding of the analogy "DNA is a blueprint." Her answer intrigued us.

> Carrie: Blueprint means, like, makes you unique or what's . . . how you?
> I: OK. A blueprint. Let me tell you what it is, then.
> Carrie: Yeah. I thought I knew what it is. OK. Just say what you . . .
> I: [As interviewer draws out a rough sketch of a blueprint on a piece of paper] OK. Let's say you're going to build a house, and before you build the house, you want to make some sort of a design, some sort of a plan, and so you draw out what the house is going to look like on a piece of paper and you draw. "We're going to put a roof here," and you put measurements next to it. The roof's going to be this big, and you draw windows and you put measurements next to them. The windows are going to be this big. So you use that picture. That's your blueprint and you use that to make the house.
> Carrie: I didn't think about that as blueprint.
> I: So, you thought a blueprint was something that makes you unique?
> Carrie: Yeah. [. . .] We do have this [blueprints], of course, in Romania.
> I: But not with associating it with that word.
> Carrie: Exactly. I didn't know that it's called in English "blueprint." [. . .] My vocabulary's so low.

As we continued to speak, Carrie explained that her instructors in Romania had said that DNA was unique or individual for each different person. When she arrived in the United States, an instructor said that DNA was a blueprint, so Carrie equated the word "blueprint" with

the word "unique." Although the analogy was meant to explain some of the characteristics of DNA by comparing the DNA to a blueprint, in the case of Carrie, the analogy had the effect of confusing her understanding of a word in English.

Analogies are potentially difficult for second-language learners to understand because translation of words from the native language to English must accompany understanding of the analogy itself. The potential of analogies to complicate students' English learning and comprehension might, therefore, be a phenomenon that should be examined further in the future.

When Do Students Avoid Using Analogies?

Although students generally use analogies from their biochemistry classes for a variety of reasons, there are certain circumstances under which students *do not* use analogies from their classes. Knowing when students do not use analogies to learn should be useful as instructors plan their use of analogies.

First, students do not tend to use analogies for biochemical concepts that they already understand or have already found a way to visualize in their heads. For example, Brent, a student in the 300-level survey course, told us what he thought about an analogy used in his class in which Velcro was compared to hydrogen bonds.

> Brent: Well, I mean . . . I don't know. Just from my chemistry classes, I have a pretty solid understanding of what exactly a hydrogen bond was. But I thought his analogy with Velcro made total sense. I don't think I ever really used it or thought of it just because in my chemistry classes I understood it. [. . .] 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. But, I mean, going over hydrogen bonds was kind of like going over something that I've already gone over two or three times.

We found that students also do not use analogies that are presented to them in their classes when they feel overwhelmed by either the amount of information they have to learn or with the short period of time in which they are expected to learn a given amount of information. We spoke to Amanda, a student in the 300-level class, two days before she was to take an exam that covered glycolysis, the citric acid cycle, oxidative phosphorylation, and photosynthesis. As we talked, Amanda expressed her anxiety about the upcoming exam. We asked her if she was using the analogies her instructor had provided to prepare for the exam, such as one in which the electron transport chain was compared to a bucket brigade. She said that she was not going to use these analogies because she was overwhelmed with the information she had to learn for the exam. She knew that her instructor would ask her questions about structures and processes, but not about analogies, so she did not study the analogies.

> 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]."

As might be expected, we found that students, in most cases, do not use analogies if they do not understand them. Many students with whom we spoke said that they did not understand all of the analogies that their instructors presented. We asked the students what they did if they heard an analogy in class that they did not understand. Most students, at all levels, said they ignored the analogy.

> Stephanie: Like, if [analogies] don't make sense to me, then it's just like, "aaah . . . whatever." It's just another thing that he can just blah, blah, blah about and I really don't pay attention to it.

Although most students ignore analogies they do not understand, there are students who spend an inordinate amount of time trying to understand analogies from their classes. Lisa, a student in the 100-level biochemistry class, said that it bothers her to not understand something her instructor says in class so she will think about an analogy until she understands it, which potentially distracts her from learning during the rest of the class period.

> Lisa: That's how I learn. I don't . . . I can't sit and memorize for hours 'cause I get bored, so I have to, like, listen to somebody tell me or read it and then think through it, figure out how it works and I got it. So, if . . . so listening to somebody give a bad analogy, I'm going to think through, "why the heck does that work with this?" and then maybe in the end, if it's right, I'll be like, "OK." But, by then, I'll be so aggravated for making me think that long, you know, I don't even want to pay attention anymore or I will have been distracted from what they were talking about later in the lecture, so . . . All bad things.

The fourth circumstance in which students do not use analogies is related to the third. Students do not use analogies *until* they understand them. Our discussions with students lead us to believe that although many analogies make sense and are useful to the students at the moment in which they are being presented, students are not able to use the analogies until they study either the analogy or the biochemical concept covered by the analogy. Brian, one of the graduating chemistry majors with whom we spoke, suggested that students do not really understand analogies until they have been forced to study the course material in preparation for a test, and many of the graduate students with whom we spoke suggested that they, also, do not understand analogies to the point at which they can explain the analogies until they have studied for an exam.

> Brian: Well, then, if I hadn't been tested on that [topic covered by the analogy], and I hadn't . . . because I don't study hard until I know that there's an exam coming, so I would have no idea what he's talking about [with the analogy].

One of the graduate students responded to a question about various analogies she had heard in her classes as follows:

> Rebecca: I remember the comparison, but without studying, I don't really remember why [the comparison was made].

This phenomenon of not understanding an analogy until they studied course material became an important theme in the analysis of the interview data collected with the 300-level biochemistry students. We interviewed about half of the volunteers from this class before their third exam and about half of the volunteers after their third exam. We asked each of these students about analogies from their class that were relevant to the information covered on their third exam. The majority of students we interviewed before the exam were unable to explain the analogies, while the majority of students we interviewed after the exam demonstrated a good understanding of the analogies.

CONCLUSIONS AND IMPLICATIONS

The students who participated in this study revealed a number of different ways they use analogies to learn and function in their biochemistry classes. Some of their analogy uses have been previously reported. For example, biochemistry students are using analogies to understand biochemistry concepts, particularly to develop an initial understanding of or to organize their thoughts about biochemical concepts, or to visualize different biochemical molecules and processes. Additionally, biochemistry students state that analogies help them to recall information during exams and motivate them to learn biochemistry.

Other ways that biochemistry students use analogies were unique and quite clever. Students report using analogies to check their understanding of their instructors' explanations or to determine what they should pay attention to in class. They also report using them to communicate with family and friends, to determine the meanings of words in English, and to determine whether their instructors care about them.

Although the literature reports that analogies can be used to help students overcome misconceptions [3, 6, 34–40], none of the students in this study mentioned using analogies for that purpose. It appears that students are not consciously aware of this important use of analogies. Accordingly, instructors who use analogies to help their students overcome misconceptions must make this purpose explicit to their students or their students are not likely to recognize why their instructors are using the analogies or use them in the manner intended by their instructors.

In comparing the ways that the students in this study use analogies to learn and the reasons biochemistry instructors gave for using the analogies in their class [10], there seem to be many similarities and one key difference. Both students and their instructors agree that analogies are useful to promote understanding and visualization of concepts, but while instructors use analogies to help students make connections—between two biochemical concepts or between a biochemical concept and concepts from other classes—students use analogies to remember information from class. Instructors did not mention using analogies to help their students remember information, and very few students mentioned using analogies to make connections between scientific concepts.

We believe that this difference in the ways in which students and instructors use analogies can be related to what they perceive as the difficulties associated with learning biochemistry. In our interviews, the students reported that one of the main difficulties associated with succeeding in biochemistry classes is the overwhelming amount of information they must learn. For students, analogies are useful because they can be used to help students remember some of that information. Instructors, on the other hand, believe that students find biochemistry difficult because they lack the necessary background to understand biochemical concepts [10]. Instructors use analogies to help their students make connections between biochemical concepts and the background knowledge they need to understand those biochemical concepts. Students may not have sufficient perspective to understand that information they have learned in previous classes may help them understand biochemistry, so they use analogies to remember information instead of to make connections between different biochemical and chemical or biological concepts even though the connections are the intended purpose of the analogies. Once again, instructors must be clear about their purposes for using analogies if they want their students to use them in the intended manner.

This conclusion is consistent with the results of previous studies. Thagard [53] states that "the use and effectiveness of analogies depends on paying close attention to what purposes they are intended to accomplish" (p. 538). Zook and Maier [54] found that students often developed misconceptions if the instructional purposes of using an analogy were not clear to them. When students were aware of the purpose of the analogy, they tended to focus their attention on appropriate relational structures between the analog and target. Similar results were seen in studies by Zook and DiVesta [55] and Mason [40].

Teaching is not an activity done in isolation. It is a collaboration between students and instructors, the results of which are better if the two groups understand each others' concerns, purposes, and actions. We believe that analogies will be more effective in biochemistry classes if instructors understand when and how their students are using analogies AND if students understand their instructors' purposes for using analogies. For example, if instructors know that their students are using the analogies from class to determine which information will be on the exam and do not use analogies when they feel they need to simply memorize information for an exam, instructors may consciously consider using analogies as part of their teaching on important topics and not using analogies for concepts that are not as important or for concepts that must be memorized. On the other hand, if students know their instructors' purposes for teaching with analogies, students will be more likely to use the analogies for the purposes their instructors intended.

Our goal in this study was to interview a large, varied population of biochemistry students in order to identify the range of ways that biochemistry students use analogies to learn and function in their biochemistry classes. Many of the ways biochemistry students use analogies correlate well with ways identified in the literature. We have, however, identified additional uses of analogies, the knowledge of which may help biochemistry instructors use analogies more effectively in their classes. While it is possible that the specific uses of analogies will vary from student to student and class to class, we believe we have identified a range of possible uses for any biochemistry class. Whether there are particular differences in the ways students use analogies to learn and function in various classes remains a matter for future research.

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APPENDIX A

Interview Guide for Students

- Background Questions
  - Tell me a little about your background.
    - How long have you been at this university?
    - What is your major? Why did you decide on that major?
    - What do you plan to do when you finish your degree?
    - What kind of biochemistry classes have you taken? How many do you have to take?
  - Tell me a little bit about your feelings about science/biochemistry.
  - What did you learn about in your biochemistry class?
  - What did you like about your biochemistry class?
  - What was the hardest part about learning biochemistry for you?
  - Tell me how you studied for your biochemistry class(es). Are there any differences between how you study for biochemistry class and how you study for other classes?
- Analogies in the Classroom Questions
  - Describe the characteristics of teachers that you learn a lot from. What about the characteristics of teachers from whom you have difficulty learning?
  - How was your biochemistry class taught? What are your feelings about how it was taught?
  - How do you think biochemistry classes should be taught? (What do you think biochemistry teachers should do to help you learn more?)
  - 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?
  - Do you remember hearing any analogies in your biochemistry class? If so, do you use them to study? How? Do they help you when the time comes to take exams? If so, how?
  - Do you like it when teachers use analogies? Why?
  - What do you think are the advantages and disadvantages of using analogies?
  - Why do you think teachers use analogies to teach?
  - What do you think your teachers want you to do with the analogies they use in class?
  - Have you noticed any analogies in your textbook? What do you think about them? (Are they useful? Do you understand them? Did your teacher refer to them?
- Analogy Questions
  - What are some of the analogies that you heard in your biochemistry class?
  - 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?
  - What biochemistry subjects are particularly difficult, abstract or challenging for you? Would analogies have helped you to learn these topics?
  - What suggestions do you have that would help teachers or textbook authors use analogies in a way that would be more useful to you?

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