JOURNAL OF RESEARCH IN SCIENCE TEACHING VOL. 43, NO. 10, PP. 1040–1060 (2006)

An Analysis of the Effectiveness of Analogy Use in College-Level Biochemistry Textbooks

MaryKay Orgill,[1] George M. Bodner[2]

[1]*Department of Chemistry, University of Nevada, Las Vegas, 4505 Maryland Parkway, Las Vegas, Nevada 89154-4003*

[2]*Department of Chemistry, Purdue University, 560 Oval Drive, West Lafayette, Indiana 47907-2084*

Received 10 September 2004; Accepted 28 June 2005

Abstract: Science instructors and textbook authors often use analogies to help their students use information they already understand to develop an understanding of new concepts. This study reports the results of an analysis of the use of analogies in eight biochemistry textbooks, which included textbooks written for one-semester survey biochemistry courses for non-majors; two-semester courses for chemistry or biochemistry majors; and biochemistry courses for medical school students. We present an analysis of how analogies are used and presented in biochemistry textbooks, and we compare the use of analogies in biochemistry textbooks to the use of analogies in other science textbooks. We also compare the use of analogies in biochemistry textbooks with the factors known to promote spontaneous transfer of attributes and relations from analog concept to target concept.© 2006 Wiley Periodicals, Inc. J Res Sci Teach 43: 1040–1060, 2006

Both written and oral analogies are used by practicing scientists and teachers to explain scientific concepts. Analogies are comparisons—between two domains that are neither completely similar nor completely different—that are used to promote transfer of a system of relationships between objects in a familiar analog domain to an unfamiliar target domain.

Textbook analogies have the potential advantage of being an omnipresent learning resource to students—a tool that the students can consult when the teacher is not available to make new information understandable. They are often included in textbooks because some students require alternative presentations of concepts to learn meaningfully (Thiele, Venville, & Treagust, 1995) or because they make the text more ''friendly'' to students (Bean, Searles, & Cowen, 1990). Because textbook authors can devote time and thought to constructing them, textual analogies also have the potential of being more complete and explicit than oral analogies presented in class.

Correspondence to: M. Orgill; E-mail: marykay.orgill@unlv.edu
DOI 10.1002/tea.20129
Published online 18 August 2006 in Wiley InterScience (www.interscience.wiley.com).

There are also potential problems associated with the use of analogies in textbooks. Text analogies are very different from oral analogies because they offer no mechanism for immediate feedback or modification for individual students or for the correction of misconceptions that students might develop from the printed analogies. For these reasons, text analogies must be presented in such a way that their explanations are very clear in order to be effective (Curtis & Reigeluth, 1984).

Textbook analogies, however, are not often explained clearly. According to Duit (1991), over half of the analogies in textbooks are not explained at all, and few analogies are explained completely. Comments from textbook authors indicate that they believe that either the students themselves should be capable of explaining the analogy or that the teachers should explain each analogy in the textbook they use to their students (Thiele & Treagust, 1995). For similar reasons, textbook authors rarely state the limitations of any analogy they present in their textbooks (Thiele & Treagust, 1995). Our experiences as students, instructors, and observers of biochemistry classes, however, suggest that teachers do not always follow or refer to the textbooks they have chosen for their classes, let alone explain the analogies in those textbooks (Mastrilli, 1997; Thiele & Treagust, 1994a).

Other reports about the use of analogies in textbooks indicate that students do not use textbook analogies unless explicitly told to take advantage of them (Bean et al., 1990). Roughly 15% of the analogies in science textbooks are identified in writing as ''analogies'' (Curtis & Reigeluth, 1984; Thiele & Treagust, 1994b, 1995), but this does not guarantee that the students will use the analogy as a learning tool or that they will know how to use the analogy as a learning tool even if they recognize it as such. Analogies are rarely mentioned in textbook introductions, even when the textbook uses many analogies (Glynn, 1991), and none of the textbooks that have been examined include an explanation of how to use analogies as a learning tool (Curtis & Reigeluth, 1984; Thiele & Treagust, 1994b, 1995). The authors of one high-school chemistry book commented that such metacognitive instruction did not belong in a textbook for 16-year-olds (Thiele & Treagust, 1995). Instruction about how to use analogies is left to the teacher, but this instruction often does not occur in the classroom. Rather, textbook authors and teachers assume that their students: (1) know how to use analogies as learning tools; and (2) know that they should apply the strategy of ''using analogies as learning tools'' when reading from their science textbooks.

Do Textual Analogies Aid Learning?

The studies that have been done on the effect of textual analogies on learning have been inconsistent; sometimes analogies have improved learning, other times they have not. Bean et al. (1990) gave high-school students text passages about enzyme catalysis. Half of the students' passages contained a simple, unexplained analogy; the other half did not. After they read the prose, the students were asked to summarize and explain concepts about enzyme catalysis. The quality of the summaries and explanations given by the two groups of students was roughly equivalent; the use of a written analogy did not improve learning under these conditions.

Gilbert (1989) followed a procedure similar to that of Bean et al. (1990). He gave ninth- and tenth-grade high-school students texts on either embryo and seed development or Mendelian genetics. Half of the readings were analogy-enriched, the other half were literal. When students were tested for recall, retention, and attitude toward learning, no significant differences were found between the two groups. It should be noted, however, that the analogies used in this study, like those used in the Bean et al. study, were fairly simple. Furthermore, they were neither explained nor was their use accompanied by an explanation of the target concept; students were

expected to spontaneously apply the analog attributes and relationships to the target without knowing anything about the target concept.

There have also been studies in which the use of textual analogies has produced mixed or positive results. Simons (1984) gave textual material on electricity to two groups of high-school students: an experimental/analogy group and a control group. After they studied the material, the students were given both comprehension and recall tests. Simons found that the students who scored high on measures of operational learning and students who were visualizers (as opposed to verbalizers) performed better when they used texts that contained analogies.

Even though the analogy group outperformed the control group on both comprehension and recall tests, they took much more time to read and study the information than did the control group. When the reading and study time were controlled, the differences between the students disappeared. Simons interpreted this evidence to mean that analogies are effective reading aids only when there is sufficient time for students to compare analogies with target concepts.

In another experiment, Simons (1984) studied the kind of information that was transferred when students who had been instructed in the use of analogies studied with analogies in a situation in which questions were distributed throughout the text that should have helped them integrate the analogy and target concepts. The factual knowledge of the two groups was the same, but the experimental group had a better understanding of relations between concepts in the target domain.

Glynn and Takahashi (1998) asserted that the inconsistency of the learning effects of textual analogies is the result of the inconsistency of the presentation of those analogies. Whereas other researchers have studied the effects of relatively simple, unexplained analogies, they studied the effects of an ''elaborate'' text analogy on learning. According to the authors, this is an analogy in which features are explicitly mapped from the analog concept to the target concept and for which verbal and imagery processes are activated by the analog. These ''elaborate'' analogies are consistent with Glynn's Teaching-With-Analogies (TWA) model, which outlines how an analogy should be presented to be effective (Glynn, 1991). Glynn and Takahashi indicated that such analogies can serve as early mental models for complex concepts until students replace those models with more sophisticated explanations.

In their study, eighth-grade students read either an elaborate analogy-enhanced text or a ''regular'' text about the cell and were then asked questions about the function of the cell parts. Students who studied with the analogies had higher recall scores that were maintained (factual retention) for at least 2 weeks. When younger students (sixth grade) were studied under the same conditions, both the recall and retention advantages were maintained with the analogy group.

The students were also asked to rate the concept they were studying in terms of importance, interest, and understandability. There was no significant difference in the importance ranking of the concept between the two groups. However, students in the analogy group ranked the concept of more interest and higher understandability than the control group.

It is apparent from the literature that textual analogies may play a role in making scientific text more accessible to students and that they can be effective and useful learning tools if they are clearly thought out and presented, if students have sufficient time to compare the analog concepts to the target concepts, and if students know how to use textual analogies as learning tools. In fact, if used well, textual analogies can play an important role in the meaningful learning of scientific concepts.

Published Textbook Analyses

Previous analyses of the use of analogies in science textbooks have focused mainly on high-school texts in the areas of general science, biology, earth science/geology, chemistry, and physics

(Curtis & Reigeluth, 1984; Thiele & Treagust, 1994b, 1995). Very few college-level science textbooks and no biochemistry textbooks have been examined previously.

The number of analogies in science textbooks is relatively small. High-school chemistry textbooks averaged eight to nine analogies per book (Thiele & Treagust, 1994b, 1995), which is comparable to the 8.3 analogies per text reported by Curtis and Reigeluth (1984) for typical general science textbooks. It should be noted that some textbooks from these studies contained up to 22 analogies per book; however, as the average number of analogies per book is approximately 8, the majority of textbooks presented in these studies must contain fewer than 8 analogies per book. This number is substantially higher than the number of analogies (2.7 per book) found in social science textbooks (Curtis, 1988); however, it is much lower than the number of analogies (43.5) found in biology textbooks by Thiele et al. (1995). The number of analogies found in each textbook may be a function of the individual preferences of the authors (Curtis & Reigeluth, 1984), or it may be a function of the manner in which a subject has traditionally been taught.

Duit (1991) noted that in physical science textbooks—which usually have the highest number of well-explained analogies—analogies are used to explain abstract or challenging information (Duit, 1991). This is consistent with the results of Thiele and Treagust (1994b), who found that analogies in chemistry textbooks were associated with concepts that are thought to be difficult or abstract for students, such as atomic structure, bonding, and energy—concepts that are difficult for students to visualize.

The notion that analogies often cover target material that is difficult or abstract is supported by the relative levels of abstraction of the analog and target concepts. Although the majority of target concepts in textbook analogies are abstract in nature, the majority of analog concepts that explain the abstract target concepts are concrete in nature (Curtis, 1988; Curtis & Reigeluth, 1984; Thiele & Treagust, 1994b; Thiele et al., 1995). Because concrete concepts are thought to be easier for students to understand than abstract concepts, a concrete analog is used, in most cases, to help students understand abstract target concepts (Curtis & Reigeluth, 1984).

The literature on textbook analogies has shown that: (1) the majority of textbook analog/target pairs share similar behaviors or relationships, as opposed to simply sharing similar external feaures; (2) the majority of analogies are explained to some extent, although they are seldom explained completely; (3) analogies are usually presented verbally, although biology and social science textbooks contain more pictorial representations of analogies than chemistry textbooks; (4) analogies are rarely accompanied by a statement of the limitations of the analogy; and (5) analogies are explicitly identified as ''analogies'' only about 15% of the time (Curtis, 1988; Curtis & Reigeluth, 1984; Thiele & Treagust, 1994b, 1995; Thiele et al., 1995). By leaving out any explicit statements that indicate the presence of an analogy or explain how analogies are used to learn concepts, textbook authors have implicitly stated their beliefs that students should know how to identify and use analogies on their own. Such spontaneous recognition and use of analogies is not often reported in the literature.

We analyzed the use of analogies in college-level biochemistry textbooks as part of a larger study of the use of analogies in biochemistry (Orgill, 2003). Observations of biochemistry classes and interviews with students enrolled in these classes have led us to believe that biochemistry textbooks are important resources for students. In our experience, most students do not rely on texts as primary sources of information under the ''ideal'' situation in which lectures are easily comprehended and concepts that are tested on course exams are easy for the student. We found that students are more likely to refer to their biochemistry textbooks when they do not understand the explanations given by their instructor; when they are struggling with challenging homework or laboratory assignments; and when they are preparing for quizzes or exams. We therefore decided to examine how effectively analogies are used in biochemistry textbooks, as determined by the

factors that have been identified in the analogy literature as promoting positive, spontaneous transfer of attributes and relations from analog concept to target concept. We also wanted to compare analogy use in biochemistry textbooks to that which has been reported for chemistry and biology textbooks.

Method

Textbooks

The biochemistry textbooks analyzed in this study were chosen on the basis of several criteria. First, we analyzed textbooks that were the primary text for the classes in which we observed analogy use (Orgill, 2003). Second, we asked several biochemistry instructors to identify exemplary biochemistry texts at the undergraduate, graduate, and medical school levels that should be included in such a study. Finally, we included one textbook because we had observed the class taught by one of the coauthors of this text.

Overall, we examined eight biochemistry textbooks. Two of the books are used in one-semester survey courses for non-majors: *Concepts in Biochemistry* (Boyer, 1999) and *Biochemistry* (Campbell, 1999). Four of the books are used in two-semester, undergraduate/graduate-level classes: *Biochemistry* (Garrett & Grisham, 1999), *Biochemistry* (Berg, Tymoczko, & Stryer, 2002), *Lehninger Principles of Biochemistry* (Nelson & Cox, 2000), and *Biochemistry* (Voet & Voet, 1995). Finally, two textbooks are used in medical school biochemistry classes: *Basic Medical Biochemistry* (Marks, Marks, & Smith, 1996) and *Harper's Biochemistry* (Murray, Granner, Mayes, & Rodwell, 2000).

Textbook Analysis

Each textbook was read, line-by-line, by the first author to examine the use of analogies therein. She started by reading the textbooks' prefaces, where she looked for information the authors provided on how analogies can be used to communicate information or learn science concepts. She read completely through the main text to identify comparisons between biochemical concepts and concepts with which students could be expected to come into contact in their daily lives. She marked all such comparisons with a flag without judging whether these comparisons were analogies or not.

There are many different types of comparisons between biochemical concepts and everyday concepts that can be found in biochemistry textbooks. Studying all of them would be a difficult task. We therefore limited the types of comparisons for study. After the first author reread each of the comparisons, she developed, through discussion with the second author, a specific list of criteria that were used to define what an ''analogy'' is for this portion of the study. The first author then read through each of the comparisons a third time and determined if each separate comparison met these criteria. The second author reviewed the decisions of the first author. We used each comparison that met the ''analogy'' criteria for the remainder of this part of this study. These criteria are described in what follows.

The first author then read through the comparisons a fourth time and made an initial categorization of each of the analogies based on a classification scheme described in the following section. After reading, she developed, through discussion with the second author, a system of rules by which the analogies were assigned to certain categories. She then reread the analogies and made changes in the initial categorization that were consistent with these rules. The second author reviewed the categorizations of the first author. In the case of analogies that appeared more than

once in a textbook, the analogy was categorized as it first appeared in the textbook and each subsequent appearance of the analogy was cross-referenced to the first appearance of the analogy.

Because we wanted to use the classified analogies to examine how analogies are used in each specific textbook and how analogies are used generally in all the biochemistry textbooks, we examined each element of the classification scheme and calculated the percentages of the analogies that met the characteristics outlined in the classification scheme. Consider one aspect of the classification scheme: ''level of enrichment,'' for example. For this aspect of the classification scheme we calculated the percentage of analogies that were ''simple,'' the percentage of analogies that were ''enriched,'' and the percentage of analogies that were ''extended.'' We calculated percentages for each book and then for all of the books together.

What Is an Analogy?

Because there are many comparisons in a biochemistry textbook that could possibly be construed as analogies, we found it necessary to place limits on the types of comparisons that we categorized as analogies in this study. Table 1 provides an outline of the criteria we used for classifying a comparison as an analogy, and we describe these criteria in detail in this section.

Table 1
Criteria used for the categorization of a statement as an ''analogy''

Criteria	Example of a Statement Considered to Be an ''Analogy''	Example of a Statement Not Considered to Be an ''Analogy''
Statement is found in the main text.	''The triple helix structure is similar to that of a rope'' (Boyer, 1999, p. 122).	''Section I deals with proteins and enzymes, the work-horses of the body'' (Murray, Granner, Mayes, & Rodwell, 2000). [This statement is found in the preface of the book.]
Statement is a comparison of a biochemical concept with an object or process with which the student could reasonably expect to come into contact through everyday experience or reading.	''Just as an energy source (electricity, gas, etc.) is required for pumping water uphill, energy must be supplied for active transport of solute molecules'' (Boyer, 1999, p. 264).	''The transport mechanism has many characteristics similar to enzyme action'' (Boyer, 1999, p. 267). [Students cannot be expected to come into everyday contact with ''enzyme action.'']
Biochemical concept in the comparison cannot be an *example* of the everyday object.	''In the energy economy of the cell, glucose reserves are like ready cash'' (Campbell, 1999, p. 573).	''More recently, it has been shown that F_1 portion of ATP synthase acts as a rotary motor'' (Campbell, 1999, p. 561). [According to *Webster's American Dictionary* (1999), the F_1 portion of ATP synthase *is* an example of a motor.]
Two objects or concepts being compared in the statement share more than just similarities in external appearances.	''Rate-limiting enzymes are like highway barriers'' (Marks, Marks, & Smith, 1996, p. 304).	''In electron micrographs, chromatin resembles beads on a string'' (Campbell, 1999, p. 260). [The structure of chromatin is not similar to beads on a string; however, a picture of chromatin *looks* like beads on a string.]

First, we analyzed comparisons that were found in the main text of the book and not in the introduction or preface of the textbook. Second, we were primarily interested in analogies in which a comparison is made between a biochemical concept (the target) and a concept or thing with which a student could reasonably be expected to come into contact through everyday experience or reading (the analog). Among the statements we read were comparisons between biochemical concepts and everyday words with analogical roots or words that had both specific and more general meanings. Determining whether or not these comparisons were analogies was difficult. We relied on definitions from the *Webster's American Dictionary* (1999) to make our decisions. For example, ATPase is often called a ''motor.'' The definition in the dictionary gives both a specific definition for a gasoline motor in a motor vehicle and a more general definition of a motor as anything that uses electricity to make something move or work (*Webster's American Dictionary*, 1999). Because ATPase is a motor by the more general definition, we determined that the statements that compare ATPase to a motor would not be considered analogies for the purpose of this study. On the other hand, cell membranes are often compared to mosaics. The definitions we found in the dictionary for ''mosaic'' were specific—they referred to pieces of art formed from small pieces of glass or stone held together by mortar. A cell membrane is not a mosaic by this definition, so we considered statements that compared cell membranes to mosaics to be analogies for the purpose of this study. Ultimately, the comparisons that we classified as analogies for the purpose of this study include metaphors, similes, and nonmathematical models as well as comparisons that could strictly be considered analogies.

We also included a third criterion for the analogies that we would consider in this research: the analog and the target should share similar behaviors or functions. They could also have similarities in external appearance, but they had to at least have behaviors or functions in common. Having said this, it may not be clear to students who are learning biochemistry for the first time that certain analog/target pairs only share external similarities. As such, students may be confused by such comparisons and assume that the analog and target share more than external features. For example, many textbooks compare the structure of chromatin to ''beads on a string'' because the electron micrograph of chromatin swelled in water shows small spheres (nucleosomes) separated by thin fibers (DNA). The statement ''beads on a string'' suggests that the DNA extends through a hollow core in the nucleosome. The structure of chromatin, however, consists of a DNA strand periodically wound around solid nucleosome cores. If students were to assume that the statement ''beads on a string'' is an accurate representation of how DNA and nucleosomes interact instead of just a description of the electron micrograph picture of swelled chromatin, they could develop incorrect conceptions of the structure of chromatin on the basis of the comparison. Although students may develop ideas based on comparisons in which the analog and target only share external similarities, we did not study these types of comparisons. Finally, we should point out that, in deciding whether a comparison should be classified as an analogy or not, we did not make a judgment about the quality of the analogy.

While making decisions about whether we would accept a particular statement as an analogy for the purposes of this study, we discovered that there were many types of statements that we would not consider analogies for study purposes. We developed a list of these types of statements to complement the criteria just given when making decisions about what we would consider to be an analogy for this study. Table 2 provides a list of these types of statements along with examples.

Classification Scheme

After determining which comparisons would be considered analogies for the purpose of this study, we classified each analogy according to a scheme we modified slightly from that of Thiele

Table 2
Types of statements listed in textbooks that were not considered analogies for the purpose of this study

Characteristics of Statement	Example of Statement
Analog and target concepts only share external similarities	''A β-pleated sheet can be visualized by laying thin, pleated strips of paper side by side to make a 'pleated sheet' of paper'' (Garrett & Grisham, 1999, p. 168).
Analog concept is not clearly matched to a specific target concept	''This relative inefficiency of the human 'engine'' leads to the production of heat as a consequence of fuel utilization'' (Marks et al., 1996, p. 714).
Anthropomorphisms	''Some proteins that bind to DNA can actually recognize specific nucleotide sequences by 'reading' the pattern of H-bonding possibilities presented by the edges of the bases in these grooves'' (Garrett & Grisham, 1999, p. 365).
Cartoon depictions without explanations	A cartoon depicts a cell as a spaceship in Voet and Voet (1995, p. 7).
Chemical analogs (substrate analogs, analogous reactions or equations, etc.)	''Suicide substrates are inhibitory substrate analogs designed so that, via normal catalytic action of the enzyme, a very reactive group is generated'' (Garrett & Grisham, 1999, p. 447).
Concepts being compared are examples of the same phenomenon	In a discussion about the potential energy of reactions, a block at the top of an inclined plane is given as an example of an object with potential energy (Nelson & Cox, 2000, p. 9).
Defined biochemical terms	''Penicillin inhibits the cross-linking transpeptidase by the Trojan horse stratagem'' (Berg, Tymoczko, & Stryer, 2002, p. 215). *Note:* Even though it has analogical roots, the term ''Trojan horse'' now has a specific meaning in biochemistry. These comparisons using defined chemical terms will not be considered analogies in this study *unless* the analog or the analogy is explained.
Descriptions of graphs using everyday words	Speaking of an energy diagram: ''This level of energy is represented by the top of the 'hill' between reactants and products'' (Boyer, 1999, p. 143).
Etymologies	''The surfaces of gram-positive bacteria are covered by teichoic acids (Greek: *teichos*, city walls), which account for up to 50% of the dry weight of their cell walls'' (Voet & Voet, 1995, p. 270).
Mnemonics	Speaking of the essential amino acids: ''Medical students sometimes use silly mnemonics to remember such lists. Here is one LIL TV To PM (HA). (Little TV tonight (PM). HA)'' (Marks et al., 1996, p. 13).
One biochemical concept compared to another chemical concept	Speaking of glucose permease: ''The transport mechanism has many characteristics similar to enzyme action'' (Boyer, 1999, p. 267).
Proverbs	''Western blotting makes it possible to find a protein in a complex mixture, the proverbial needle in a haystack'' (Berg, Tymoczko, & Stryer, 2002, p. 103).
Symbols that represent a molecule or parts of a molecule	''The letters A, G, T, and C correspond to the nucleotides found in DNA'' (Murray et al., 2000, p. 452).
Target is not a biochemical concept	''The camel, the renowned 'ship of the desert,' provides a striking example of adaptation involving the erythrocyte membrane'' (Voet & Voet, 1995, p. 301).
Target is compared to a situation that does not independently exist	''A peptide backbone can be visualized as a series of playing cards, each card representing a planar peptide group. The cards are linked at opposite corners by swivels, representing the bonds about which there is considerable freedom of rotation'' (Campbell, 1999, p. 111).

and Treagust (1994b), who based their classification scheme on one originally developed by Curtis and Reigeluth (1984). Since the development of the initial classification scheme by Curtis and Reigeluth (1984), four additional studies have reported analyses of textbook analogies using this scheme or some modification of the scheme. Although the original study (Curtis & Reigeluth, 1984) was an analysis of many different kinds of science textbooks at different levels, the subsequent studies have been analyses of social science textbooks (Curtis, 1988), high-school chemistry textbooks (Thiele & Treagust, 1994b, 1995; Thiele et al., 1995), and high-school biology textbooks (Thiele et al., 1995). No study has focused specifically on college textbooks of any kind.

We chose to use this classification scheme with little modification because several chemistry, biology, and general science textbooks have been analyzed according to the scheme, and we wished to compare the results of our analysis to previous work to determine whether analogies are used differently in biochemistry textbooks. Each element of the classification scheme identifies features of the analogy that may promote meaningful learning of scientific concepts. The classification scheme is outlined, with corresponding examples, in Table 3. The reasoning behind each element of the scheme, and our modifications to the scheme are presented in what follows.

Table 3
Criteria used for the classification of analogies

Criteria	Criteria Definition	Example of Analogy That Meets Criterion
3. Analogical relationship between analog and target: A: Structure–function; B: Function	The two concepts compared in the analogy share: A: Similarities in external features/ appearance and similarities in behaviors or functions; B: Similarities in behaviors or functions only.	A: ''The triple helix structure is similar to that of a rope'' (Boyer, 1999, p. 122). [The structure of collagen looks like a rope.] B: ''In electron transport the flow of electrons is from one compound to another rather than along a pipe, but the analogy of a blocked pipeline can be useful for understanding the workings of the pathway'' (Campbell, 1999, p. 561).
4. Presentation format: A: Verbal; B: Verbal–pictorial	Analogy is presented: A: In words only; B: In words and in picture form.	A: ''The ATP expenditure at the beginning of the glycolytic pathway is sometimes called 'priming the pump' because it gets the pathway going'' (Marks et al., 1996, p. 342). B: ''Metabolic regulation is achieved through an exquisitely balanced interplay among enzymes and small molecules, a process symbolized by the delicate balance of forces in this mobile'' (Garrett & Grisham, 1999, p. 460). [A picture of a mobile accompanies the analogy.]

5. Level of abstraction: A: Concrete: abstract; B: Abstract: abstract; C: Concrete: concrete	The first word refers to the analog concept. The second word refers to the target concept. Concrete concepts are those students could see, touch, smell, or feel in their everyday lives.	A: ''Studies on enzyme specificity carried out by Emil Fischer led him to propose, in 1894, that enzymes were structurally complementary to their substrates, so that they fit together like a 'lock and key'" (Nelson & Cox, 2000, p. 251). [Locks and keys are concrete; enzymes and substrates are not.] B: ''Circe effect: The utilization of attractive forces to lure a substrate into a site in which it undergoes a transformation of structure, as defined by William P. Jencks, an enzymologist, who coined the term'' (Berg et al., 2002, p. 206). [Students would not be expected to see, touch, smell, or feel Circe—or her pigs—in their everyday lives.] C: There were no examples of this kind of analogy in the biochemistry textbooks.
6. Position of analog relative to target: A: Advanced organizer; B: Embedded activator; C: Post-synthesizer	A: Analogy is presented prior to the main text of the chapter containing the primary discussion of the target concept. B: Analogy is presented in the main text of the chapter which contains the main discussion of the target concept. C: Analogy is presented in a chapter after the main discussion of the target concept.	A: ''In the energy economy of the cell, glucose reserves are like ready cash'' (Campbell, 1999, 573). [Analogy is presented in introduction to chapter about glycolysis, not in the main text of the chapter.] B: ''Why is phosphofructokinase rather than hexokinase the pacemaker of glycolysis?'' (Berg et al., 2002, p. 447). [Analogy is presented in the main text of the chapter about glycolysis.] C: ''We have previewed the transfer pathway, DNA → RNA → proteins; we began our detailed journey with DNA, the storehouse of all genetic information'' (Boyer, 1999, p. 350). [Analogy is presented in a chapter after the main discussion of DNA.]
7. Level of enrichment: A. Simple; B. Enriched; C. Extended.	A: Analogy does not include a statement of either describing the purpose for using an analogy or explaining the connections between analog and target concepts. B: Analogy includes a statement of either describing the purpose for using an analogy or explaining some of the connections between analog and target concepts. C: An analogy that was used multiple times throughout a text.	A: ''The temperature at the midpoint of this process is known as the protein's melting temperature, T_m, in analogy with the melting of a solid'' (Voet & Voet, 1995, p. 179).

		B: ''Proteins include specific sequences that serve as address labels to direct the molecules to the proper location'' (Berg et al., 2002, p. 339). [Analogy statement explains why the protein sequences are like address labels.] C: ''Thus, anabolic and catabolic processes are coupled together through the mediation of the universal biological energy 'currency,' ATP'' (Voet & Voet, 1995, p. 17). [The analogy that compares ATP to currency was used 10 times in this text.]
8. Analog explanation	The analog (familiar) concept in the analogy is at least partially explained.	''The STATS are then phosphorylated on Tyr residues by the same Janus kinase (hence the name Janus—like the mythological figure, the kinase has two 'faces')'' (Nelson & Cox, 2000, p. 898).
9. Indication of cognitive strategy	Textbook authors identify the presence of the analogy with the word ''analogy.''	''This so-called rack mechanism (in analogy with the medieval torture device) was based on the extensive evidence for the role of strain in promoting organic reactions'' (Voet & Voet, 1995, pp. 379–380). [The torture rack is being compared to the conformational strain that occurs during transition state binding.]
10. Limitations of the analogy	Textbook authors describe where the analogy breaks down.	''The enormous success of recombinant DNA technology means that the molecular biologist's task in searching genomes for genes is now akin to that of a lexicographer compiling a dictionary, a dictionary in which the 'letters' that is, the nucleotide sequences, spell out not words, but genes and what they mean. Molecular biologists have no index of alphabetic arrangement to serve as a guide through the vast volume of information in a genome; nevertheless, this information and its organization are rapidly being disclosed by the imaginative efforts and diligence of these scientists and their growing arsenal of analytical schemes'' (Garrett & Grisham, 1999, p. 419).

Our modification of the ''Analogy Classification Framework'' (Thiele & Treagust, 1994b) classifies analogies within the following areas:

1. *The content of the target concept*: Are there specific biochemistry concepts that tend to be taught with analogies? Are there specific biochemistry concepts that are not taught with analogies?
2. *The location of the analogy in the textbook*: Is the analogy found at the beginning of the textbook, in the middle of the textbook, at the end of the textbook? We divided each textbook into ten equal parts by page numbers and assigned each analogy to one of those parts.
3. *The analogical relationship between analog and target*: Analogies for which the analog and target concepts share similar relational structures, in which the function or behavior of the analog and target are the same, are said to have similar ''function,'' according to Thiele and Treagust. Analogies for which the analog and target concepts share both similar relational structure and similarities in external features are said to have similar ''structure-function,'' according to Thiele and Treagust. The original classification scheme presented by Thiele and Treagust also includes ''analogies'' in which the analog and target concepts share only similarities in external features, or object attributes. The two domains in this type of comparison are said to have similar ''structure.'' However, because we do not consider comparisons that are based solely on similarities in external appearance to be ''analogies,'' we did not include shared ''structure'' as part of our modified analogy classification scheme.
4. *The presentation format*: Is the analogy presented verbally (in words) or is it presented verbally and pictorially? We did not look for a pictorial representation of the target concept, but for a pictorial representation of either the analog concept or of the analogy—a picture that compares the analog concept to the target concept.
5. *The level of abstraction of the analog and target concepts*: Is the analog abstract or concrete? Is the target abstract or concrete? We considered a concept concrete if it was something that students might see, hear, or touch with their eyes, ears, or fingers in the course of their daily activities. All other concepts were considered to be abstract. Necessarily, then, concepts such as mythological figures that a student might read about but not directly experience were considered to be abstract concepts unless a picture of the mythological figure showing the traits to be transferred from analog to target was provided with the verbal account of the analogy.
6. *The position of the analog relative to the target*: Is the analog presented before the target concept as an ''advanced organizer,'' with the target as an ''embedded activator,'' or after the target, as a ''post-synthesizer''? We considered an analogy to be an ''embedded activator'' if the analogy was presented in the main text of the chapter in which the primary discussion of the target concept was found. We considered it to be an ''advanced organizer'' if the analogy was presented either in a chapter that preceded the primary discussion of the target concept or in a chapter preface where the preface was separated from the main text of the chapter. We considered the analogy to be a ''post-synthesizer'' if it was presented after the main discussion of the target concept. In all cases, we referred to the textbooks' tables of contents to determine which chapter contained the main discussion of the target concepts.
7. *The level of enrichment*: How much mapping is explicit? Is the analogy ''simple,'' ''enriched,'' or ''extended''? We categorized each analogy as either ''simple'' or ''enriched.'' The analogy was ''enriched'' if the analogy statement included either a reference to the reason for which an analog was being compared to a target concept or a statement of explicit mapping between objects in the analog and target domains, even if the mapping between domains was not complete. All other analogies were classified as

"simple." In addition to being categorized as "simple" or "enriched," an analogy that was used multiple times throughout the text was also categorized as "extended."

8. *Analog explanation*: Is the analog concept explained in any detail? For this category, we did not require a complete explanation of the analog concept. Instead, we looked for any explanation of the analog concept beyond the name of the analog concept.
9. *Indication of cognitive strategy*: Do the textbook authors indicate that they are using an analogy to explain a concept with the word "analogy"?
10. *The limitations of the analogy*: Do the authors state any limitations of the analogy?

Results and Discussion

Textbooks: General Findings

We found a total of 158 comparisons that met our criteria for classification as analogies in the eight biochemistry textbooks we read, ranging from a low of five analogies in one book to a high of 35 analogies in another. This average of 19.75 analogies per biochemistry book is much higher than the average number of 8.45 analogies found in secondary chemistry books (Thiele & Treagust, 1994b, 1995). It is also higher than the average number of 8.3 and 2.7 analogies in general science and social science textbooks, respectively (Curtis, 1988; Curtis & Reigeluth, 1984). However, the average number of analogies in biochemistry texts is approximately half of the 43.5 analogies per book found in secondary biology textbooks (Thiele et al., 1995). Overall, there were similar numbers of analogies per page for the books designed for one-semester survey courses for non-majors and those for two-semester undergraduate/graduate-level courses. There were significantly fewer analogies in the medical-school textbooks; however, the medical school books contain many more clinical examples of phenomena than the other biochemistry books, and the clinical examples may play an educational role similar to that of analogies.

Somewhat surprisingly, there were few differences in how analogies are used and presented in the different level books. Analogy use did not depend on the level of the book as much as it did on the style of the individual books. For example, two of the texts were more likely to position analogies as advanced organizers and present more analogies pictorially than other books (Berg, Tymoczko, & Stryer, 2002; Garrett & Grisham, 1999). Both of these books contained chapter prefaces in which a nonbiochemical concept—for which a picture was provided—was compared with a topic to be presented in the following chapter. Overall, however, analogy use was similar from book to book and from level to level, with the exception of the biochemistry textbooks written for medical school students.

The presentation of analogies in biochemistry textbooks is less than the ideal described by Glynn and Takahashi (1998). None of the textbooks contained instructions about how to use analogies as a cognitive strategy even though most contained a description of the pedagogical improvements and aids used in the textbook. There was not a single analogy in any of the textbooks that was presented as effectively as it could be, according to the Teaching-With-Analogies model (Glynn, 1991). Even the use of the word "analogy" was not consistent from book to book. In two of the textbooks (Murray et al., 2000; Voet & Voet, 1995), the words "analogy" and "analogous" were sometimes used to mean "similar" instead of "analogous." Consider the following excerpt, for example: "Analogous examples of reciprocal benefit between biochemistry and medicine could be cited" (Murray et al., 2000).

Glynn and Takahashi (1998) stated that written analogies can promote learning when used appropriately. In the next sections, we compare the presentation of analogies in these biochemistry

textbooks with the features that are known to promote meaningful learning of scientific concepts and with the presentation of analogies in other types of science textbooks.

Textbook Analogy Categorization

Table 4 contains a summary of the categorization of analogies in the biochemistry textbooks we examined. We compare the results of the current study to those of previous studies in this section.

Target concepts. Gick and Holyoak (1983) suggested that analogies should be written for difficult or hard-to-visualize concepts because analogies become extra information for students to learn when concepts are easily explained by other means. Thiele and Treagust (1994b) found that the main topics covered by analogies in high-school chemistry textbooks were atomic structure, bonding, and energy—all difficult or hard-to-visualize concepts. The target concepts for analogies in biochemistry textbooks are also hard to visualize, and target topic coverage appears to be roughly consistent from one textbook to another. As in chemistry books, many analogies relate to energy, both in terms of reaction energetics and in terms of the energetics that drive cellular processes. The storage and transfer of genetic information in DNA is another target concept for which many analogies have been presented in biochemistry textbooks. Other concepts covered by analogies include the complementarity of enzymes and their substrates, the general functions and behaviors of proteins, basic cell membrane structure, membrane transport, the regulation of metabolism, and various biotechnology topics.

There are several specific analogies that are repeated in the majority of the biochemistry textbooks examined in this study. Mitochondria are repeatedly described as ''the powerhouses of the cell.'' The binding of an enzyme to its substrate is often compared to a lock and a key (''lock-and-key model''). A cell membrane is often compared to a mosaic piece of art (''fluid mosaic model''). ATP is often referred to as a ''cellular energy currency'' in discussions of metabolism and reaction coupling. The processes of DNA translation and transcription are often discussed in terms of the translation and transcription of a language. Metabolic regulation is often explained by comparison to a system of water pipes in which particular valves can control the flow of water through the pipes. Although these analogies are generally the analogies that are referred to multiple times in the biochemistry textbooks examined here, they are usually not explained to any great degree. It is possible that it has become so common to refer to and explain these target concepts in terms of their corresponding analogies that textbook authors assume that little explanation of the terms is needed. Whether this is true is a question for future research.

Perhaps as interesting as the target concepts for which there were analogies are the target concepts for which there were no analogies. The biochemistry textbooks examined in this study presented the same major topics, only varying in the depth of their discussion of those topics. Analogies were lacking or few for the topics of buffers, three-dimensional protein structure, carbohydrates, lipids, metabolic reactions and processes, and photosynthesis. There also do not appear to be any analogies for biochemistry topics that involve calculations, such as acid/base chemistry and enzyme kinetics. Many of the concepts for which there are no analogies have been identified by instructors as topics with which students have difficulty. It is unclear, however, whether these topics are intrinsically more difficult than other topics discussed in biochemistry, or if the manner in which these topics are presented in the classroom and in textbooks contributes to students' difficulty with them.

Location in textbook. Overall, more analogies are found in the beginning of biochemistry textbooks than at the end of these books. In fact, the general trend is that the number of analogies decreases from the beginning to the end of the textbook. This is consistent with Thiele and

Journal of Research in Science Teaching. DOI 10.1002/tea

Table 4
Categorization of analogies in biochemistry textbooks (B, C, S, G, L,V, M, H)[a]

		B	C	S	G	L	V	M	H
Total number of analogies		15	21	27	22	18	35	5	15
3. Analogical relationship	Function	80.0%	95.2%	96.3%	81.8%	77.8%	74.3%	60.0%	66.7%
	Structure-function	20.0%	4.8%	3.7%	18.2%	22.2%	25.7%	40.0%	33.3%
4. Presentation format	Verbal	100%	95.2%	74.1%	63.6%	83.3%	94.3%	80.0%	93.3%
	Verbal—pictorial	0.0%	4.8%	25.9%	36.4%	16.7%	5.7%	20.0%	6.7%
5. Level of abstraction	Concrete: abstract	100%	95.2%	88.9%	90.9%	94.4%	97.1%	100%	100%
	Abstract: abstract	0.0%	4.8%	11.1%	9.1%	5.6%	2.9%	0.0%	0.0%
	Concrete: concrete	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
6. Position of analog relative to target	Advanced organizer	0.0%	23.8%	40.7%	50.0%	11.1%	5.7%	0.0%	0.0%
	Embedded activator	86.7%	61.9%	59.3%	50.0%	83.3%	94.3%	100%	93.3%
	Post-synthesizer	13.3%	14.3%	0.0%	0.0%	5.6%	0.0%	0.0%	6.7%
7. Level of enrichment	Simple	40.0%	47.6%	29.6%	31.8%	27.8%	45.7%	20.0%	60.0%
	Enriched	60.0%	52.4%	70.4%	68.2%	72.2%	54.3%	80.0%	40.0%
	Extended	33.3%	14.3%	29.6%	31.8%	16.7%	20.0%	0.0%	20.0%
8. Analog explanation?		0.0%	42.9%	33.3%	45.5%	33.3%	28.6%	20.0%	13.3%
9. Indication of cognitive strategy?		0.0%	33.3%	14.8%	18.2%	11.1%	28.6%	0.0%	33.3%
10. Indication of limitations?		6.7%	4.8%	3.7%	9.1%	5.6%	2.9%	0.0%	0.0%

[a]B: Boyer (1999); C: Campbell (1999); S: Berg, Tymoczko, and Stryer (2002); G: Garrett and Grisham (1999); L: Nelson and Cox (2000); V: Voet and Voet (1995); M: Marks et al. (1996); H: Murray et al. (2000).

Treagust's (1994b) findings with secondary chemistry texts. They suggested that textbook authors might believe that students need analogies to help them initially become acquainted with the new topics and words presented in the beginning of a textbook. As students become familiar with the language and concepts of the discipline, however, toward the end of a semester or the end of a textbook, they may not require as many analogies to help them understand biochemical concepts. Instead, they can reference new biochemical information to information they have learned previously in the course or in the textbook.

This assumption, however, might not be true in the case of biochemistry textbooks. In all of the textbooks in this study, except Marks, Marks, and Smith (1996), a relatively large number of analogies are presented in the introductory chapters. For the rest of the book, however, the analogies are not specific to a location in the textbook, but to topics presented in the textbook. For example, all textbooks have analogies about enzyme/substrate complementarity, so the sections of the textbook that include the topic of enzymes contain analogies. On the other hand, not a single analogy was found about carbohydrates or lipids in any of the textbooks; the sections of the book that cover these topics do not contain as many analogies, no matter where the chapter is placed in the textbook.

Analogical relationship between the analog and the target. The majority of analogies presented in biochemistry textbooks link analog and target concepts that share functions or behaviors. This was also true of the analogies in secondary chemistry, science, and social science books (Curtis, 1988; Curtis & Reigeluth, 1984; Thiele & Treagust, 1994b). Overall, there is a slightly higher percentage of biochemistry analogies where the analog and target share function (79.0% of total analogies) than in the other types of textbooks presented in the literature (60.0%).

Gentner's (1983, 1989) structure-mapping theory suggests that the stronger, more useful analogies are those with a lot of overlap in behavioral or functional features. The current study and previous studies with secondary science and social science textbooks suggest that the majority of analogies presented in textbooks do show great overlap in behaviors and function. The question that has not been sufficiently examined in this or other studies is whether students who are unfamiliar with the topics in a discipline are capable of determining which analog/target pairs share only structure or external similarities in the absence of explicit cues. If students do not recognize that two concepts being compared share external similarities, they may transfer functional or behavioral traits from analog to target domains and, thus, develop misconceptions about the target domain.

Presentation format. Almost all analogies in biochemistry textbooks are presented in verbal format. Only 23 of the analogies we examined contain a pictorial representation of either the analog concept or the analogy and, of these, only one analogy is depicted in both verbal and pictorial format. The rest of the pictorial depictions are of analog concepts. Most of the pictorial analog depictions are presented in chapter prefaces. Those not presented in chapter prefaces are drawn in the margins of the text. In general, there are more pictorial representations of analogies in secondary chemistry and biology textbooks (Thiele & Treagust, 1994b; Thiele, Venville, & Treagust, 1995) than in the college-level biochemistry books examined in this study.

Previous experiments have suggested that including an appropriate visual representation of an analogy—one that depicts the analog features that are to be transferred to the target domain—can promote analogical transfer (Beveridge & Parkin, 1987), but textbooks, especially those studied here, do not tend to include such pictures. Curtis and Reigeluth (1984) found similar results in their study of elementary- and secondary-level science books, and their conclusion was that a visual representation of an analogy was useful, but that verbal explanations of an analogy were, perhaps, sufficient for promoting analogical transfer. Studies with analogies, however, showed that spontaneous transfer of written analogies only occurs under particular conditions, as outlined by

Glynn and Takahashi (1998). For a written analogy to be as effective as it can be, the presentation of the analogy must include not only a presentation of the analog concept, but explicit mapping of the analog and target concepts, an explicit statement of the limitations of the analogy, and an explicit statement of the conclusions that can be made about the target concept based on the analog concept. As will be shown, very few presentations of analogies in biochemistry textbooks include any statement of the limitation of the analogy or an explicit mapping between domains.

Level of abstraction of the analog and target concepts. Nearly all of the analogies presented in these biochemistry textbooks demonstrate a concrete analog domain for an abstract target domain. The remainder of the biochemistry analogies compare an abstract analog to an abstract target; and, in each of these cases, the analog concept is a mythological or literary figure that we consider to be abstract.

The majority of analogies in other types of secondary books also compare a concrete analog to an abstract target; however, these other kinds of books also contain a significant number of analogies in which a concrete analog is compared to a concrete target concept (Curtis, 1988; Curtis & Reigeluth, 1984; Thiele & Treagust, 1994b; Thiele et al., 1995). This is particularly true in the case of secondary biology textbooks (Thiele et al., 1995). We did not find any analogies of this last kind. Biochemistry concepts, for the most part, cannot be seen and do not lend themselves to being concrete.

One of the hypothesized roles that analogies play is that of helping students concretize or visualize difficult or abstract concepts (Dagher, 1995; Harrison & Treagust, 1993; Simons, 1984; Thiele & Treagust, 1994a; Venville & Treagust, 1997). This suggests that textbook analogies will be more useful when a concrete analogy is compared to an abstract target concept, because the analogy can provide a concrete reference to which the student can refer when thinking about the biochemical concept (Brown, 1993; Simons, 1984). Most biochemistry textbook analogies do this.

Position of the analog relative to the target. There are three potential positions of an analog concept relative to a target concept, and each of these placements has potential educational advantages and implications. An analog can be placed before a target concept as an ''advanced organizer'' that can prepare a student for the introduction of a new concept. An analog can be introduced with the target concept, as an ''embedded activator.'' In such a position, an analogy can not only help students come to an understanding of a target concept, but may also highlight certain aspects of the target concept, making students focus on these aspects more. Finally, an analog can be presented after a target concept as a ''post-synthesizer'' to help students recall the target concept and begin to connect that concept with other target concepts.

In biochemistry textbooks, most analogies are embedded activators (78.6%), presented in the main text of the chapter that contains the discussion of the target concept. Three of the textbooks (Campbell, 1999; Garrett & Grisham, 1999; Berg, Tymoczko, & Stryer, 2002) presented numerous analogies as advanced organizers, most of these being presented in chapter prefaces and not necessarily in chapters that preceded the main discussion of a topic. Very few analogies are presented as post-synthesizers in any of the books.

Results from other studies of textbooks also indicate that the majority of analogies are presented as embedded activators (Curtis, 1988; Curtis & Reigeluth, 1984; Thiele & Treagust, 1994b). Curtis and Reigeluth (1984) suggested that this overwhelming positioning of analogies as embedded activators indicates that analogies are most useful when presented with the main discussion of their target concepts. This implication, however, is not supported by any evidence except for the fact that analogies in textbooks are usually presented in this position. To our knowledge, no research has been done examining this position. The effects of placing the analogies in different positions relative to the target concept should be examined at a future date in order to determine the most effective placement of analog concepts in written analogies.

Level of enrichment. Over half of the analogies in the biochemistry texts were found to be enriched (explained) to some degree. This does not indicate that the analogies are completely enriched/explained, but that those analogies contain at least one explicit mapping between objects in the analog and target domains or one explicit indication of why the analog and target domains are being compared. In fact, none of the analogies we looked at is completely explained. Although there are similar percentages of enriched analogies in social science textbooks (Curtis, 1988), there are more enriched analogies in general science textbooks (Curtis & Reigeluth, 1984), fewer enriched analogies in secondary chemistry books (Thiele & Treagust, 1994b, 1995), and even fewer enriched analogies in secondary biology books (Thiele et al., 1995). Ideally, analogies should be completely explained or enriched if they are to be understood (Curtis & Reigeluth, 1984; Glynn & Takahashi, 1998), but this is not the case for any of the analogies that we found.

Approximately one fifth of the analogies we found are used multiple times in a given textbook (''extended''). There are similar percentages of extended analogies in secondary chemistry, science, and social science textbooks (Curtis, 1988; Curtis & Reigeluth, 1984; Thiele & Treagust, 1994b, 1995), but it is clear that the researchers who analyzed the other types of textbooks did so in a slightly different manner than we did. They analyzed analogies as either ''simple,'' ''enriched,'' or ''extended.'' Their definitions of ''simple'' and ''enriched'' are equivalent to our definitions, but ''extended'' referred to a situation where one analogy covers multiple topics or multiple analogies are used to explain one topic. We felt there was a difference between how often an analogy is used in a textbook and whether the analogy is explained, so we separated them into two categories. Although our definitions are slightly different, these results do indicate that a significant number of analogies in educational textbooks are used repeatedly throughout the text. Although all analogies should be explained in a text to be effective in promoting meaningful learning, it is even more important to explain those analogies that appear multiple times in the text because they potentially influence a student's understanding of multiple biochemical topics.

Pre-topic orientation. There are certain factors that promote analogical transfer that are not directly related to the analogy. Transfer is facilitated if the comparison is explicitly identified as an ''analogy,'' if the analog domain is explained, and if the limitations of the analogy are made explicit. Unfortunately, these features are not usually present in biochemistry textbook analogies. On the average, only one-fourth of analog domains are explained in biochemistry textbooks. This is much less than the 58% of analog domains that are explained in other secondary science books (Curtis & Reigeluth, 1984; Thiele & Treagust, 1994b, 1995).

Perhaps the authors of biochemistry textbooks assume that the analog domains they use are so familiar or so simple that they require no further explanation. Reading through the analogies, we identified several analog concepts which required no more explanation than the name of the analog domain. For example, one analogy compares an enzyme and its substrate to a glove and a hand. The words ''glove'' and ''hand'' gave us all the information we needed about the analog domains to understand the analogy, and we believed that such things would need no further explanations for other students. In our interviews with students who were unfamiliar with the target concept, however, we discovered that even simple analog domains require some clarification (Orgill, 2003). In the case of the hand and the glove, students wanted to know what kind of glove and how big a hand the instructor was referring to because the students were not sure if they were picturing the same thing in their minds as their instructor. Some of these problems could have been avoided had a visual representation of the analog domain been provided.

Analogies are only explicitly identified as ''analogies'' about 15% of the time in science textbooks (Curtis & Reigeluth, 1984; Thiele & Treagust, 1994b, 1995; Thiele et al., 1995) and about 17% of the time in biochemistry textbooks. As such, students may not recognize that the comparison they are reading is an analogy—that the two domains being compared do share some

similar traits but are more dissimilar than similar. There are a number of ways in which the authors of the textbooks in this study introduce analogies in their books other than using the words ''analogy'' or ''analogous.'' Table 5 provides a list of some of the phrases they use and examples of their use. Many of the phrases used suggest that the analog and target domains are similar to each other without giving any indication of the dissimilarities between the two domains or of the limitations of the analogy. This is unfortunate because students who do not understand that a comparison is limited may transfer irrelevant features of the analog to the target domain.

Table 5
Alternative phrases used in biochemistry textbooks to indicate the presence of an analogy

Phrases	Example
''acts as,'' ''plays the role of''	''This is because these membraneous sacs are encased on their outer (cytosolic) face by a polyhedral framework of the nonglycosylated protein clathrin, which is believed to act as a flexible scaffolding in promoting vesicle formation'' (Voet & Voet, 1995, p. 310).
''akin''	''The enormous success of recombinant DNA technology means that the molecular biologist's task in searching genomes for genes is now akin to that of a lexicographer compiling a dictionary, a dictionary in which the 'letters,' i.e., the nucleotide sequences, spell out not words, but genes and what they mean'' (Garrett & Grisham, 1999, p. 419).
''are,'' ''is''	''In fact, many proteins are mosaics of sequence motifs which occur in a variety of other proteins'' (Voet & Voet, 1995, p. 132).
''as,'' ''just as''	''Just as an energy source (electricity, gas, etc.) is required for pumping water uphill, energy must be supplied for active transport of solute molecules'' (Boyer, 1999, p. 264).
''for much the same reasons''	''A substrate of the wrong chirality will not fit into an enzymatic binding site for much the same reasons that you cannot fit your right hand into your left glove'' (Voet & Voet, 1995, p. 326).
''in the same way,'' ''in the same manner''	''Heat must also be path-dependent. It is therefore meaningless to refer to the heat or work content of a system (in the same way that it is meaningless to refer to the number of one dollar bills and ten dollar bills in a bank account containing $85.00)'' (Voet & Voet, 1995, p. 44).
''is/are compared to''	''The complementarity between the substrate and its binding site is compared to that of a key fitting into a rigid lock'' (Marks et al.,1996, p. 102).
''is/are sometimes called,'' ''is/are termed''	''The ATP expenditure at the beginning of the glycolytic pathway is sometimes called ''priming the pump'' because it gets the pathway going'' (Marks et al., p. 342).
''like,'' ''likened to,'' ''is/are like''	''An important method of communication between cells is the transmission of chemical signals through ion channels, pores in transmembrane proteins that can be opened and closed like gates'' (Boyer, 1999, p. 270).
''model''	''The lock-and-key model assumes a high degree of similarity between the shape of the substrate and the geometry of the binding site on the enzyme'' (Campbell, 1999, p. 152).
put analog term in quotation marks	''Each enzyme has, in fact, a miniature 'operating table' where the substrate is momentarily held in a predetermined position so that it can be cut or altered with surgical precision. The scene of the operation, called the active site, is usually a groove, cleft, or cavity on the surface of the protein'' (Campbell, 1999, p. 145).
''similar,'' ''similarly''	''The concept of 'spontaneity' [···] is similar to water held behind a dam at the top of a hill, which has potential energy to flow downhill, but it will not do so unless someone opens the dam'' (Campbell, 1999, p. 401).
''think of''	''Think of the metabolic pathways as networks of pipelines in which the flow of material may be in either direction'' (Boyer, 1999, p. 468).

Even if an analogy is identified as such and even if the students recognize that all analogies have limitations, they may not be able to identify the particular limitations of a given analogy. Theoretically, an analogy is used to facilitate the understanding of new information by comparing it to already familiar information. Students who are unfamiliar with the target domain cannot possibly know the limitations of an analogy unless those limitations are made explicit. However, of the 158 analogies we collected from biochemistry books, only seven limitations of analogies were found, and six of these refer to a single analogy that occurs in multiple textbooks (the ''lock-and-key'' model of enzyme/substrate binding).

Conclusions

Overall, the manner in which biochemistry analogies are used and presented in biochemistry books is very similar to their use in the secondary textbooks that have been the subject of analyses described in the literature. Furthermore, analogy use does not differ greatly with the level of textbook.

Although textbook authors use a significant number of analogies as learning aids in each of their textbooks, the authors do not present the analogies in the most effective manner. None of the analogies are completely explained, very few are identified as ''analogies,'' and the limitations of the analogies are rarely mentioned. Textbook authors may assume that biochemistry instructors will explain the analogies that are present in their textbooks, but this is not the case; the textbook authors must provide explanations of their analogies if they believe students can effectively use these analogies to learn biochemistry concepts.

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