DOCUMENT RESUME

ED 349 164 SE 052 951

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TITLE Using Analogies To Aid Understanding in Secondary Chemistry Education.

PUB DATE Jul 91

NOTE 14p.; Paper presented at the Royal Australian Chemical Institute Conference on Chemical Education (Perth, Western Australia, Australia, July 1991).

PUB TYPE Speeches/Conference Papers (150) -- Guides - Classroom Use - Teaching Guides (For Teacher) (052))

EDRS PRICE MF01/PC01 Plus Postage.

DESCRIPTORS *Chemistry; Foreign Countries; Science Education; *Science Instruction; Secondary Education; *Secondary School Science; *Textbooks

IDENTIFIERS *Analogies; *Analogy; Australia

ABSTRACT

Analogies are believed to help students structure new knowledge and are considered to be especially useful for topics of an abstract or submicroscopic nature. Analogies, however, have also been identified as a factor in the students' misunderstanding of chemical concepts. This paper reports on the literature identifying the advantages and constraints of the use of analogies in chemistry education. The term "analogy" is defined and three types of analogies--verbal, picture, and personal--are described. Analogies are used in three major ways: to provide visualization of abstract concepts, to compare similarities of the students' real world with the new concepts, and to provide a motivational function. The following constraints of analogies are described: analog unfamiliarity, stages of cognitive development, and incorrect transfer of attributes. An examination of analogies found in textbooks currently used by Australian high school students is discussed with respect to these identified advantages and constraints. Results of the content analysis revealed that only 4.3 percent of the books had specific warnings or limitations on the use of analogies. Only 21 percent of the analogies presented included any statement identifying the strategy such as "an analogy," "analog," or "analogous." This study concludes that textbook authors may be underestimating the difficulties that students encounter when attempting analogical transfer. (Contains 15 references.) (PR)

Using analogies to aid understanding in secondary chemistry education

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In assisting students to understand chemistry concepts, teachers occasionally use analogies. These analogies are believed to help the students to structure the new knowledge and they are considered to be especially useful for topics of an abstract or submicroscopic nature. However, analogies have also been identified as a factor in the students' misunderstanding of chemical concepts.

This paper reports on the recent literature identifying the advantages and constraints of the use of analogies in chemistry education. Specifically, an examination of analogies found in textbooks currently used by Australian high school students is discussed with respect to these identified advantages and constraints.

INTRODUCTION

To assist in the explaining of abstract chemical concepts, teachers may help their students achieve conceptual understanding, rather than algorithmic understanding, by employing teaching tools such as analogies and models. An analogy can allow new material to be more easily assimilated with the students' prior knowledge enabling those who do not readily think in abstract terms to develop an understanding of the concept. Over the last decade, heightened interest concerning the use of analogies in science education has resulted in the presentation of a clearer picture of the types of analogies that are available and their ranges of presentation style.

However, it is still evidenced that the use of analogies does not always produce the intended effects. Teachers occasionally discover that students take the analogy too far and are unable to separate it from the content being learned. Other students only remember the analogy and not the content under study whilst yet others focus upon extraneous aspects of the analogy to form spurious conclusions relating to the target content. This paper considers a decade of research literature concerning the use of analogies in science education and presents some of the advantages and the constraints of using analogies in chemistry instruction by making reference to a thorough examination of analogy examples found in Australian high school chemistry textbooks.

DEFINING AN ANALOGY

There is a need to clearly define what an analogy is so that it is not confused with illustrations and examples. Glynn et al. [1] provide a useful working definition:

> An analogy is a correspondence in some respects between concepts, principles, or formulas otherwise dissimilar. More precisely, it is a mapping between similar features of those concepts, principles, and formulas. (p. 383)

The analogy requires the selection of a student world <u>analog</u> to assist in the explanation of the content specific <u>target</u> (or topic). The analog and target share <u>attributes</u> that allow for a relationship to be identified. A diagrammatic representation of the analogical relationship is shown in Figure 1.

ANALOGICAL RELATIONSHIP

ANALOG ....compared with ....TARGET
Attribute   Attribute
1....................compared with....................1
2....................compared with....................2
3....................compared with....................3
n....................compared with....................n

Figure 1. Analogical relationship between the analog and the target illustrating the sharing of attributes (Adapted from Glynn et al., 1989, p. 384).

One analogy that has been used in chemistry textbooks to help explain aspects of the region of influence of an electron is that of a rotating propeller. [2,3,4] In this analogy, the target concept is an understanding of the characteristics of an electron's region of influence. The analog is a description, or diagram, of a rapidly rotating plane propeller. There are several shared attributes that are readily compared. When the propeller is rapidly rotating, it is not possible to state exactly where the blade is at any given instant and yet, if a person was to attempt to insert a stick into the general area, they would find that the propeller's properties are applied throughout the whole region. Similarly, the electron, due to its rapid motion and wavelike properties, exerts its presence throughout a large orbital region without being specifically present at any exact location at any given instant. This comparison of shared attributes is known as mapping. It involves a deliberate categorization of those attributes that are shared between the analog and the target. It is also true that there are attributes of both the rotating propeller system and the area of electron influence that are not shared. For example, the propeller is fixed in its orbit of rotation, whereas the electron is mobile within a probablistic three-dimensional orbital. It must be considered that the analog and the target will have many attributes that are not shared. Good mapping should also give indication as to where this occurs so that unshared attributes are not ascribed to the target domain.

Discussions relating to the use of analogies in chemistry education found in educational literature have indicated the confusion that is occasionally shown when differentiating analogies from illustrations and examples. This is highlighted in several articles, for example Remington [5], which present different methods of illustrating the magnitude of the Avogadro number or the mole. As the Avogadro number is a number that need not be subject specific, illustrations showing how thick a layer of Avogadro's number of marbles would coat the earth do not ideally match the definition of an analogy presented by Glynn et al. but are better considered as illustrations or perhaps examples. However, an analogy for the mole that is better aligned with Glynn et al's. definition is found in Garnett [6]:

> Just as it is convenient to group eggs into cartons of a dozen or sheets of paper into reams (500 sheets), chemists measure the amount of any substance in terms of moles. (p. 41)

In this analogy, the analog is dozens and reams while the target concept is the mole. The attribute shared by both the analog and the target is the grouping of substance for convenience.

DIFFERENT TYPES OF ANALOGIES

The literature [7] highlights a range of types of analogies which include verbal, pictorial, personal, bridging, and multiple analogies, some of which are discussed below. Further, Curtis and Reigeluth [8], in an analysis of 52 analogies from four American chemistry textbooks, proposed several other criteria by which analogies may be further classified by their integral parts. In developing these criteria, Curtis and Reigeluth give further credence to the viability of analogy use in chemistry education. These criteria include an analysis of the nature of the shared attributes (structural or functional), the degree of explanation concerning the analog, as well as the level of enrichment of the analogy (the extent to which the author mapped the shared attributes). It is also evident that the final presentation by the classroom teacher will have a considerable influence upon the mode of operation of an analogy.

Verbal and Pictorial Analogies

Verbal analogies include only written text or oral presentation. As this type of analogy is often subtly embedded in the body of the text, the reader is usually left to draw the necessary comparisons and conclusions about the target from the description of the analog. Alternatively, a pictorial analogy allows the textbook author or teacher to pictorially highlight the desired attributes of the analog. This method helps provide a greater degree of visualization which reduces the likelihood that the student is not sufficiently familiar with the analog. Figure 2 is an example of a pictorial analogy for the propeller/electron relationship discussed above. Most pictorial analogies are accompanied by some verbal explanation and hence, technically should be referred to as pictorial-verbal analogies. Unfortunately, the extra space required for pictorial analogies in textbooks can be a limiting factor to their frequency of use.

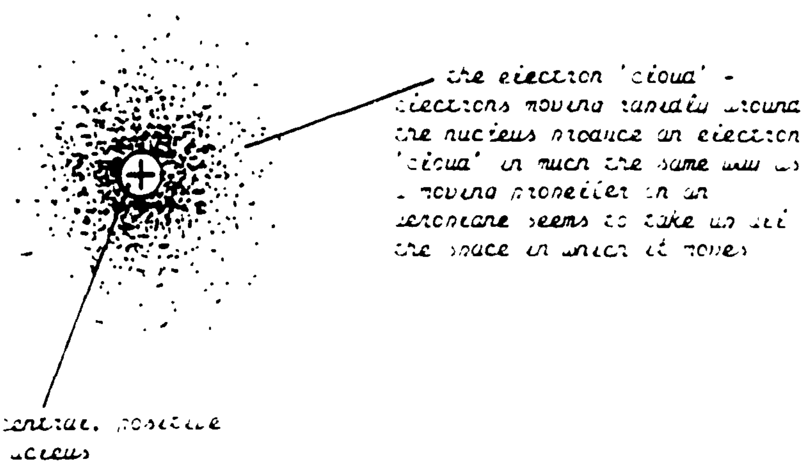


Figure 2. A pictorial analogy.
Taken from *A Guide to H.S.C. Chemistry* (p. 1) by P. Lewis and R. Slade, 1981, Melbourne, VIC: Longman Cheshire Pty Limited. Copyright 1981 by Longman Cheshire Pty Limited. Reprinted by permission.

Personal Analogies

This type of analogy is believed to assist students by relating abstract chemical concepts to student world considerations such as people money, food, and relationships. Students can be physically involved in a personal analogy. For example, chemistry students may be asked to walk around the classroom in such a manner that their direction of travel is analogous to the motion of electrons through a wire or ionic migration through a solution during electrolysis. Alternatively, the students may only be involved at a mental level. In this situation, they could consider the packaging of sausages and rissoles into barbecue packs to be analogous to a reacting system and the effect of a limiting reagent on the amount of product and excess reagent remaining. Marshall [9] suggests that this type of analogy causes better learning of concepts and that the approach is more enjoyable although she cautions that personal analogies can cause students to give intuitive feelings to inanimate objects and concepts.

THE ADVANTAGES OF ANALOGIES IN TEACHING

Analogies are believed to help in three major ways in that they: a) provide visualization of abstract concepts; b) help compare similarities of the students' real world with the new concepts; and c) have a motivational function.

Visualization Process

Researchers [1,10] agree that the visualization process is very important in the learning of concepts and that the pictures prompt a visualization process to aid understanding. In an analysis of 216 analogies found in science textbooks for secondary students, Curtis and Reigeluth [8] found that chemistry textbooks contained the highest percentage of pictorial analogies (29%) compared to the total science average of only 16%. Other studies [11,12] have also highlighted the considerable use of pictorial analogies in chemistry textbooks.

Real World Linkage

The use of analogies is well linked to science in both historic and contemporary settings. Further, it has been proposed that analogies are traditionally used both in explaining science and in the processes of science. Well renowned theorists such as Maxwell, Rutherford, and Einstein are reported to have used analogical reasoning as a tool to aid problem solving and to explain hypotheses relating to early theories of atomic structure. [3,10] In a similar way, analogies are used more frequently when the target domain is most difficult to understand.[7] The presentation of a concrete analog in this situation facilitates understanding of the abstract concept by pointing to the similarities between objects or events in the students' world and the phenomenon under discussion.

Motivational Function

The motivational sense of analogy is due to a number of factors. As the teacher or textbook author is drawing from the students' real world experience, a sense of intrinsic interest is generated. In addition to this interest, students who traditionally perform at lower academic levels are more likely to achieve a level of conceptual understanding that is more substantial than usual. This results in a motivational gain. However, it should be noted that little has been determined from empirical studies about the actual learning processes that are associated with analogy assisted instruction since most of the studies have only measured the students' recall of learned materials. It is also not well known if analogies really do assist students to attain a level of conceptual understanding or whether students only use the analogy as another algorithmic method to obtain the correct answer.

THE CONSTRAINTS OF ANALOGIES

Despite the advantages and usefulness of analogies as previously outlined, the use of this teaching tool can cause incorrect or impaired learning due to some fundamental constraints related to the analog - target relationship. Three of these constraints are discussed in this paper.

Analog Unfamiliarity

A significant constraint on the use of analogies in teaching is the possible unfamiliarity of the learner with the analog selected. Several empirical studies on the use of analogical reasoning in chemistry instruction, for example a study by Gabel and Sherwood,[13] have been hindered by this problem. The finding that a significant proportion of the students sampled in these studies did not understand the analog shows clearly the need for caution in teaching with this method and in evaluating those analogies that are presented to improve student understanding of chemistry concepts.

Stages of Cognitive Development

A second area of constraint with analogy usage relates to the Piagetian stages of cognitive development. Whilst there is general agreement that analogies can assist students who primarily function at lower cognitive stages, if these students lack visual imagery, analogical reasoning, or correlational reasoning, then the use of analogies is still believed to be limited. [13] In addition, those students already functioning at a formal operational level may have attained an adequate understanding of the target and the inclusion of an analogy might add unnecessary information loads that could also result in new misconceptions being formed by the students. For these reasons, some instructors choose not to use analogies at all and thereby avoid these problems while, at the same time, they forsake the advantages of analogy use.

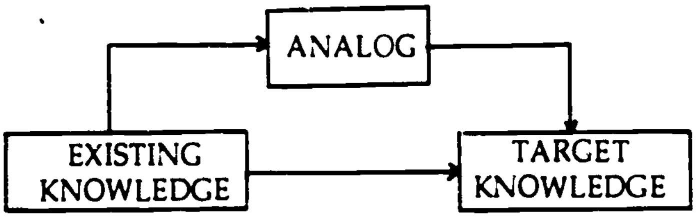
Incorrect Transfer of Attributes

The nature of the analog is that it has some shared attribute(s) with the target. However, Licata [14] considers that the unshared attributes are as instructive to the students as are the shared attributes. No analog shares all its attributes with the target as, if it did, then the analogy would become an example by definition. These attributes that are not shared are often a cause of misunderstanding for the learners if they attempt to transfer them from the analog to the target. Another related constraint occurs when the students attempt attribute transfer in an inappropriate manner. Rather than using the analog attributes as a guide for drawing conclusions concerning the target, the students occasionally incorporate parts, or all, of the analog structure into the target content. This is illustrated diagrammatically in Figure 3.[11] One of the results of this incorrect transfer is that students, when questioned concerning the nature of the target content, will answer with direct reference to analog features

When analogies are used during classroom instruction, discussion should take place to assist in the delineation of boundaries and to aid concept refinement. [14,15] Indeed, Glynn et al. [1] have produced a six step Teaching With Analogies (T.W.A.) model that is designed to assist teachers use analogies effectively This model provides for a clear delineation of shared and unshared attributes by the teacher. Allowing for student involvement and discussion at the classroom level will also provide feedback to the instructor if incorrect attribute transfer has occurred. Teachers should not assume that the students are capable of effecting correct analogical transfer but, rather, should provide explicit instruction on how to use analogies and provide opportunity for considerable classroom discussion on the subject.

ANALYSIS OF ANALOGIES USED IN CHEMISTRY TEXTBOOKS

Eight chemistry textbooks were closely examined and all analogies identified were photocopied and further analysed. The textbooks used in the analysis had been identified by state syllabus organisations as those current, generally used textbooks for Australian senior secondary chemistry education. Only one of the textbooks was not published in Australia - that was a British publication. A list of those textbooks examined may be found in an appended reference list.



Desired use of analog to show the relationship between the existing and target knowledge structures. Analog attributes are used to draw conclusions concerning the target.

Undesired effect due to the incorporation of the analog into the framework relating existing knowledge to target knowledge

Figure 3. Incorporation of analog in new knowledge. [11]

A portion of text or a picture was considered to be analogical if it was aligned with the working definition stated above and/or it was stated by the author as being analogical. Each analogy was scrutinized concerning the following features, three of which (c,d, and e) were reported by Curtis and Reigeluth:

a) the content of the target concept,
b) the location of the analogy in the textbook,
c) whether it was verbal or pictorial,
d) evidence of further explanation of the analog domain;
e) the extent of the mapping done by the author; and
f) the presence of any stated limitation or warning.

A total of 70 analogies were identified from eight textbooks. The number of analogies found in each book varied considerably with four books having less than six analogies whilst the other four had between 12 and 17 analogies. Each analogy was further examined independently by the two researchers with an original agreement of 93% for the classifications. The remaining 7% of the classifications were agreed upon following consensus discussions.

Content Analysis

The content area of the target concepts was classified into 13 categories. Table 1 indicates that a considerable proportion of the analogies (16, 23%) relate to "Atomic Structure" - including electronic arrangement. Other areas in which analogies were used more frequently were found to be "Energy" - including collision theory - (10, 14%) and "Bonding" (7, 10%). The submicroscopic nature of these target concepts emphasizes the visualization role of analogies. For example, an analogy classified under the heading "Energy" was the rolling ball analogy for activation energy. This is shown in Figure 4 as it appears in the text *Chemical Science* (Hunter et al., 1981: p. 251).

Table 1.
Analysis of the frequency of analogy use compared to target content area.

Content Area	n	%
Acids & Bases	5	7.1
Analytical Methods	3	4.3
Atomic Structure	16	22.9
Biochemistry	6	8.6
Bonding	7	10.0
Chemical Equilibrium	5	7.1
Energy	10	14.3
Nature of Matter	6	8.6
Organic	1	1.4
Periodic Table	2	2.9
Reaction Rates	3	4.3
Solutions	2	2.9
Stoichiometry	4	5.7

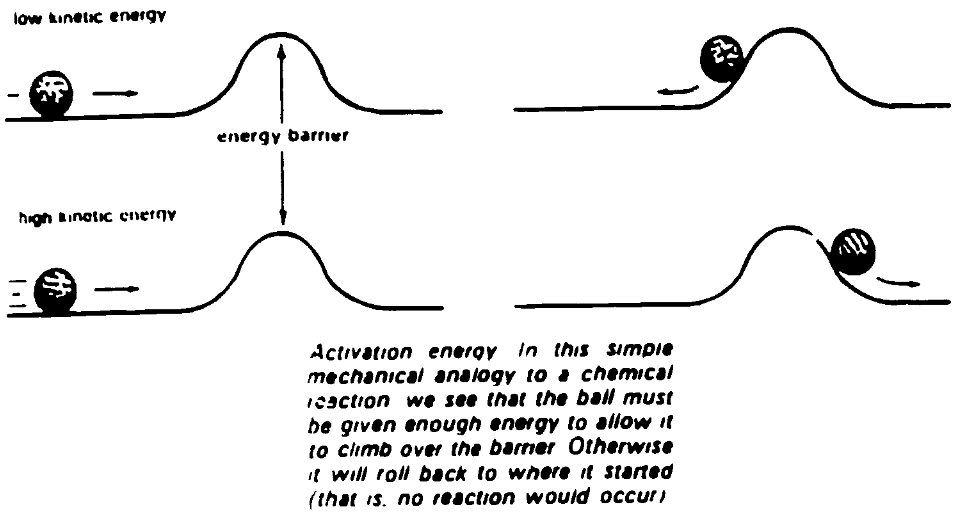


Figure 4. The rolling ball analogy for activation energy
(Hunter et al., 1981, p. 251)

Analogy Location in Textbook

The page number of each analogy was used to determine a decile measure of the analogy's location within the textbook as a whole. Table 2 suggests that the analogies tend to be used more frequently in the earlier stages of the textbook except for a number in the 7th decile. This could indicate that conceptual targets are encountered in two phases - initially when the new work is being introduced and also, at a later phase, when more difficult concepts are being presented

Table 2.
Analysis of the decile position of the analogies in the textbooks as a whole.

Location	n	%	Cum %
0	7	10.0	10.0
1	14	20.0	30.0
2	6	8.6	38 6
3	10	14.3	52.9
4	7	10.0	62.9
5	9	12.9	75.8
6	1	1 4	77.2
7	12	17.1	94 3
8	3	4.3	98.6
9	1	1.4	100.0

Verbal and Pictorial Analogies
It was found that 28 (40%) of the identified analogies had a pictorial component. These pictorial analogies, such as those illustrated in Figures 2 and 4, include some diagrammatic representation of either the analog or the target. Further analysis revealed that pictorial analogies are frequently positioned in the margin as an anecdotal package of helpful information. However, as Table 3 illustrates, verbal analogies are rarely found in a marginalized position. This indicates that authors may wish to use pictorial analogies more frequently but tend not to sacrifice the copy space. Those authors writing texts with marginalized comments tend to make use of the opportunity to use this space for pictorial analogies

Table 3.
The frequency of use of marginalized and pictorial analogies in the textbooks.

	Marginalized	Text Body	Total
Verbal	2	40	42
Pictorial	14	14	28
Total	16	54	70

Further Analog Explanation
To avoid the problems of analog unfamiliarity and incorrect attribute transfer, some writers provide background information concerning the relevant attributes of the target domain. This analog explanation attempts to ensure that the student is focussing upon the appropriate attributes at the time of analogical transfer. The explanation may constitute a simple phrase of only a few words through to a paragraph thoroughly explaining the relevant analog attributes. For example, in Figure 2, the author suggests that the moving propeller "...seems to take up all the space in which it moves", and again in Figure 4, reference is made to the ball requiring "...enough energy to allow it to climb over the barrier. Otherwise it will roll back to where it started...". Both of these statements are elementary examples of analog explanation. It was found that 40 (57%) of the analogies had some analog explanation. This is a little lower than other researchers have reported in prior studies (66 - 69%).[8,11]

The Extent of Mapping

The extent of mapping that is done by the textbook authors was classified using Curtis and Reigeluth's [8] criteria of "Level of Enrichment" as follows:

a) Simple - states only "target" is like "analog" with no further explanation;
b) Enriched - indicates some statement of the shared attributes; and
c) Extended - involves several analogs or several attributes of one analog used to describe the target.

The suggestion, as per Rutherford, that the electrons are distributed around the nucleus of an atom like the planets around the sun (Ainley et al., 1981: p. 129), would be an example of a simple analogy. In Figure 4, the inference that the ball rolling back to where it started relates to an unsuccessful collision would be an example of an enriched analogy whilst the following quotation illustrates an extended analogy (which also includes considerable analog explanation):

> An electron in an atom is therefore rather like a book in bookcase with a number of shelves. If a book is on the bottom shelf and you want it on a higher shelf, you have to do work to lift the book against its own mass and therefore some of your energy will be transferred to the book so that its potential energy will be increased. Now suppose the book slips off the higher shelf and falls down to the bottom shelf again. The energy which was given to the book, will be lost by it and given to the surroundings, probably in the form of heat. The shells in an atom are similar to the shelves in the bookcase and, just as the shelves represent different levels of potential energy above the ground, whose potential energy can be considered to be zero, the shells can be thought of as energy levels for electrons outside the nucleus which, like the ground, has a potential energy of zero. Just as it would not be possible to have a book hanging, unsupported, between two shelves in a bookcase, so it is not possible to have an electron between two shells in the atom. However, it must be remembered that, unlike a shelf, an energy shell does not have any physical existence of its own. (Ainley et al., 1981: p 135)

The textbook analysis found that the use of simple analogies is still fairly common (33, 47%) despite some research suggesting that students require assistance when relating the correct analog attributes to the target. [13,15] Only 30 (43%) of the analogies were enriched whilst the remainder (7, 10%) were extended. Further, with reference to Table 4, it was noted that three of the four textbooks having 12 or more analogies contained considerably more simple analogies than enriched analogies.

Limitations

Given that analogies can be used incorrectly by students, it has been suggested that authors should include some warning as to the limitations of the analogical process. Subsequently, each analogy was examined to see if it included.

a) A general statement of the limitation of analogy use; or
b) A statement relating specifically to the unshared attributes in the analogy.

The bookcase analogy quoted above for electron energy shells includes the statement that "... unlike a shelf, an energy shell does not have any physical existence of its own.". This is an example of a specific limitation stated at the end of the analogy to assist with the delineation of shared and unshared attributes

Table 4.
The variation in the extent of mapping of analogies found in textbooks.

Text	Simple	Enriched	Extended	Total
A	10	6	1	17
B	0	1	0	1
C	0	3	2	5
D	1	2	0	3
E	8	3	1	12
F	1	3	0	4
G	4	9	1	14
H	9	3	2	14
Total	33	30	7	70

It was found that no general statements concerning analogy use were made in any of the textbooks. In addition, only 3 (4.3%) specific warnings or limitations were expressed. This would suggest that authors are either assuming that the students are capable of effecting the analogical transfer themselves or that the teacher - in the course of normal classroom teaching - will assist in this regard

Further, it was found that only 15 (21%) of the analogies included any statement identifying the strategy such as "an analogy", "analog", or "analogous" such as is found in Figure 4. We consider that if the strategy was identified more frequently, then the effect would be similar to the addition of a warning in that it will direct students towards the correct cognitive procedure [1]

CONCLUSIONS

From this study of analogies in textbooks used in Australian schools, it is possible to draw conclusions with respect to the stated advantages and constraints of using analogies. The considerable use of pictorial analogies adds credence to the visualization effect of analogies since this helps the author communicate the nature of the shared attributes to the student more effectively. As simple analogies comprise a substantial proportion of the total, textbook authors may be underestimating the difficulties that students encounter when attempting analogical transfer. Research suggests that authors and editors should employ enriched, rather than simple, analogies for all but the most elementary relationships if the target concepts are to be better understood as a result of using the analogy. Similarly, research suggests that analogies used in textbooks where there is a lack of instruction or assistance in using the analogical processes and a scarcity of stated limitations are less useful than the authors might desire. However, it is likely that the authors have assumed that the classroom teacher will accept that responsibility, but there is little research to document the outcome of this occurrence.

Further research is required if we are to more fully understand the mental processes that students employ when using analogies. A study that focuses on both the teachers' and students use of analogies will allow for better curricular design that includes analogies that will further aid students' understanding of chemistry concepts. In addition, these studies should report not only on the end result of analogy use (such as those by Gabel and Sherwood) but also on the processes as they occur. For this reason, interview and observation techniques will be most applicable. Further research is needed on how students use analogies in learning complex chemistry concepts so as to advise authors and teachers concerning the more effective use of analogies both in textbooks and in the classroom. As it is generally assumed that teachers' repertoires of analogies are primarily derived from their reading of textbooks, and given the time taken to produce textbook materials, the advice to authors should command a higher priority.

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