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A Comparative Analysis of Analogies in Secondary Biology and Chemistry Textbooks Used in Australian Schools

Rodney B. Thiele, Grady J. Venville and David F. Treagust
Curtin University of Technology

Abstract

To aid the explanation of abstract science concepts, authors of textbooks employ learning tools such as analogies to help students learn. Analogies are believed to allow new material to be more easily assimilated with students' prior knowledge by linking it to their previous experiences. Continuing research on analogies in science textbooks and science teaching is providing a clearer picture of the types of analogies that are available (Duit, 1991), their ranges of presentation style (Curtis & Reigeluth, 1984; Thiele & Treagust, 1992), and their efficacy to effect students' conceptual understandings (Harrison & Treagust, 1993).

An analogy requires the selection of an analog to assist in the explanation of a content specific target, both of which share attributes that allow a relationship to be identified. Analogy has been defined by Glynn, Britton, Semrud-Clikeman and Muth (1989) as "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)."

This comparison of shared attributes, known as mapping, involves a deliberate categorisation of those attributes that are shared between the analog and the target. Due to the nature of analogy, however, there are attributes of both the analog and the target that are not shared. Good mapping should indicate also where this occurs so that students do not ascribe unshared attributes (i.e., limitations) to the target.

Analogies are believed to help learning in three major ways: they provide visualisation of abstract concepts, they compare the new concepts with phenomena in students' real world, and they have a motivational function (Duit, 1991). Despite the advantages and usefulness of analogies, they can cause incorrect or impaired learning due to some fundamental constraints related to the analog/target relationship. These constraints, which include students being unfamiliar with the analog employed, result in unshared attributes of the analog being ascribed to the target concept. In the case of a textbook, there is a heightened risk that the analogy may be incorrectly utilised by the students because the contents of textbooks are rarely discussed by teachers and students in the classroom (De Jong & Acampo, 1992).

Prior studies into how analogies are used in the teaching and learning of science have tended to be discipline-specific in context. The ability to generalise across science disciplines will depend upon the suitability and effectiveness of the same type of analogies in another discipline. Little is currently known about how the context of the science discipline influences the nature of analogies used in textbooks or classroom discourse. Previous research has involved an analysis of analogies in textbooks for senior science and general science (Curtis & Reigeluth, 1984), chemistry (Thiele & Treagust, 1992), and science and social science (Curtis, 1988). Glynn (1989) used instructional design characteristics to develop the Teaching-With-Analogies model after examining exemplary analogies in science textbooks. In Curtis and Reigeluth's (1984) study, textbook analogies were classified by the nature of their component parts and the relationships between analog and target concepts. This classification was extended by Thiele and Treagust (1992) by adding criteria to reflect research arguing the need for textbook authors to map overtly, provide clear statements of the limitations, and explicity to describe the analog domain employed.

It has long been acknowledged that science varies markedly in its methods and outcomes when compared with other high school subjects. Within the sciences, considerable differences exist in the subject matter, teaching approach, practical applicability, or degree of difficulty - all of which impinge upon students selection and success in each of the sciences at the senior high school level.

Many students believe that biology is an easier subject than chemistry; a belief underscored by the observation that chemistry is generally chosen by more academically able students. Chemistry is considered difficult to understand because students have trouble visualising the abstract components which are an integral part of chemistry content. Despite the beliefs of students, biological concepts such as genetics, homeostasis, and ecological interdependence also require a considerable degree of abstract reasoning (see for example, Harrison and Treagust (1994)). Shayer and Adey (1981) have commented about the cognitive demands of these two science subjects. They support the notion that biology contains many abstract concepts, arguing that a high level of demand is expected if students are correctly to make the connections between key ideas. They also argue that biological concepts are capable of some realisation at almost any cognitive level (p. 98). This contrasts with chemistry which they believe "cannot be presented in a form simple enough so that any particular learner can understand it. Since the first act of chemistry [they refer here to the concept of compound] involves formal modelling, this science has a high entrance fee compared with the two other traditional sciences."

The inclusion of analogies into high school science textbooks is founded on the premise that students require an alternative representation of some concept or entity. This premise can be further broken down into two notions that, while evidently related, may be treated as two different issues for the purpose of this paper. The first notion is that analogies are used to aid in the explanation of difficult, abstract science concepts - suggesting analogy use to be a function of the subject matter of science. The second is that students who have difficulty understanding and visualising science concepts require assistance that may be provided by analogies - suggesting analogy use to be a function of student learning. Hence, the frequency with which authors include analogies within textbooks may be due either to their own perceptions of the nature of the subject matter or to their experience with the type of students who read the textbooks and their knowledge of how these students learn. In this study on analogies, biology and chemistry textbooks were compared and any differences explained in terms of the nature of the disciplines.

Method

Four biology and ten chemistry textbooks (see Appendix) were closely examined and all analogies identified were photocopied and further analysed. Textbooks used in the analysis were identified by Australian State syllabus organisations as being recommended for senior high school biology and chemistry students and were considered representative of the textbooks most students were currently using. A portion of text or a picture was considered to be analogical if it was aligned with the working definition stated above. Each analogy was carefully scrutinised and classified according to the following four criteria: the nature of the shared analog and target attributes; the presentational format of the analogy; the degree of abstraction of the analog and target; and the extent of mapping. Figure 1 summarises descriptions of the four criteria employed.

Nature of shared attributes	
structural	the shape, size, colour, etc., of the analog is transferable to the target
functional	the function or behaviour of the analog is attributed to the target
structural/functional	analog and target share both structural and functional attributes
Pictorial representation	
verbal	analog in textual format only
pictorial/verbal	analog in pictorial format to some extent
Analog/target abstraction	
concrete/concrete	concrete analog and target
abstract/abstract	abstract analog and target
concrete/abstract	concrete analog and abstract target
Extent of mapping	
simple	states only "target" is like "analog" with no further explanation
enriched	indicates some statement of the shared attributes
extended	involves several analogs or several attributes of one analog used to describe the target

Figure 1. Summary description of classification criteria.

A more detailed description of the complete analogy classification framework can be found in Thiele and Treagust (1994).

Results and Discussion

A total of 174 biology analogies and 93 chemistry analogies were identified from the four biology and ten chemistry textbooks, respectively, and examined independently by the researchers in terms of the above four criteria (see Figure 1). An original agreement of 92% for the classifications occurred with the remaining 8% of the classifications agreed upon following consensus discussions. The summary for the classification results is found in Table 1.

Table 1
Summary of the Analogy Classifications for Four Biology and Ten Chemistry Textbooks Used in Australian Schools

	Biology		Chemistry	
	n (=174)	(%)	n (=93)	(%)
Nature of shared attributes				
structural	33	19	16	17
functional	92	53	45	48
structural/functional	49	28	32	35
Pictorial representation				
verbal	168	97	49	53
pictorial - verbal	6	3	44	47
Analog/target - abstraction				
concete/concrete	59	34	7	7
abstract/abstract	7	4	5	5
concrete/abstract	108	62	81	88
Extent of mapping				
simple	105	61	42	45
enriched	51	29	35	38
extended	18	10	16	18

In these commonly used Australian secondary science textbooks, analogies were included more frequently in the biology textbooks (an average of 43.5 analogies per textbook) than in the chemistry textbooks (an average of 9.3 analogies per textbook). This result contrasts sharply with earlier research which reported only 4 analogies per biology textbook (Curtis & Reigeluth, 1984). In the latter study, however, the textbooks analysed were from the 1960's and 1970's from the USA and had a range of year levels from Year 2 to college.

Nature of the shared attributes

The biology and chemistry analogies had similar proportions of structural, functional, and structural/functional type analogies (see Table 1). One structural analogy that was found in several chemistry textbooks related the structure of an atom to a flea or marble in the centre of a large sports field.

> If we were able to enlarge an atom so that its outer boundary was as large as that of the Melbourne Cricket Ground [which seats 100 000 people around a field 600 feet long and 400 feet wide], the nucleus would be the size of a flea on the cricket pitch. ... The comparison of a flea and the Melbourne Cricket Ground shows that the volume of the nucleus is a very small part of the volume of an atom. (Bucat, 1983, p. 36)

In this analogy, there has been no attempt to map any behavioural or functional attributes - only structural attributes have been matched. This is particularly useful when the authors wish to indicate some proportional representation of size or shape as above.

Functional analogies are those in which the function, but not the structure, of the analog is compared to the target. In biology, these tend to be of systems or biological processes, such as respiration in the example below.

> The amount of oxygen used by a guinea pig was almost the same as that needed to burn an amount of wood that produced the same amount of heat. They concluded that oxygen was being used by the body in a very slow form of burning. As happens in a fire, organic compounds were being combined with oxygen. Carbon dioxide and water were being produced, and chemical energy converted to other forms of energy, including heat. (Morgan, 1981a, p. 15)

On examination of the photocopied records, it appeared that the chemistry analogies of the structural/functional type were used to describe the function of an entity, often an electron, where both the analog's structure and function were attributed to the target concept. For example, one structural/functional analogy related to the use of double sided sticking tape to adhere a photograph into a photograph album (Ainley, Lazonby, & Masson, 1981, p. 140). This analogy was used to describe the manner in which electrons between two nuclei attract both nuclei simultaneously, thus keeping the molecule together.

Many metaphoric terms were found in the biology textbooks that, had they been classified as analogic, would have been classified as structural/functional analogies. Examples of these include 'shovel-like feet,' 'pouch-like bill,' 'file-like radula' in snails, and 'whip-like flagella.' Despite having some structural/functional attributes, these terms were not considered to be explicit enough to be instructional analogies. Rather, they convey something of the language of biology in a manner that may have equivalence in chemistry to terms such as a family of hydrocarbons, an energy barrier, and a catalysed reaction route. These terms often appear in italics, quotation marks or, as shown above, with a hyphenated term such as like. An expression such as 'an activation energy barrier' does indicate some analogic sense that may have been present at the early stages of the development of the concept but is now part of the language of the science and is no longer considered analogical.

Pictorial representation

Forty seven percent of the chemistry analogies and 3% of the biology analogies had a pictorial component which also included some kind of non-verbal representation of the analog. Diagrams or pictures of the target concept alone were not considered by the researchers to be pictorial analogies even when they were associated with a verbal analogy.

One of the reported reasons why analogies are used in the explanation of science is that they provide a framework through which a concept may be visualised. The visualisation requirement is particularly necessary when the analogy describes invisible structures and processes that are not readily observed by the students. Further visualisation may be provided with a pictorial analogy which allows the author to include only those analog attributes that they want students to focus on. The use of pictorial analogies in biology textbooks was infrequent to say the least - especially when compared to their very frequent use in the chemistry textbooks. One explanation for this scarcity of pictorial biology analogies could be related to the number of motivational pictures or photographs which are common in biology textbooks. In contrast, chemistry textbooks have pictures of, say, molecular structures, but these have less meaning and lack motivational outcomes.

These trends may be reversed in the near future, however, as advances in scanning, tunnelling electron microscopy may provide clear pictures of molecular structure. Already, chemistry textbooks recently published in Australia (Elvins, Jones, Lukins, Miskin, Ross, & Sanders, 1990; James, Derbogosian, Bowen, & Auteri, 1991) include many interesting colour pictures taken from electron micrographs, which augers well for future chemistry textbooks. Advanced computer modelling technology may also provide students with visualisation aids. Consequently, researchers may observe a decrease in the use of pictorial analogies in the chemistry textbooks of the next decade due to the trends indicated above.

Analog/target abstraction

Eighty eight percent of chemistry analogies comprised a concrete type analog for an abstract target (see Table 1). In the double-sided sticky tape analogy for electrons and bonding referred to above, the concrete idea of sticking tape was used to illustrate the abstract concept of negatively charged electrons being between, and holding together, two positively charged nuclei. The high proportion of this type of analogy found in the chemistry texts is likely to be due to the high level of abstraction of some chemistry concepts. Seven percent of the analogies had a concrete target and analog (concrete/concrete) and only 5% had both an abstract analog and target (abstract/abstract). Biology analogies had a lower proportion of concrete/abstract analogies (62%) than chemistry though the frequency of concrete/concrete analogies was markedly higher (34% compared to 7%). The difficulty of observing some concrete phenomena in biology, such as peristalsis as in the following example, may be responsible for the greater frequency of this kind of analogy.

> Behind the mass of food the muscles contract. Consequently the food is squeezed along in somewhat the same way that the last of the toothpaste can be squeezed from a toothpaste tube. The process is called peristalsis. (Morgan, 1981b, p. 568)

Historically, the basic concepts of biology such as heredity were taught in an abstract context. The trend has been to encourage teachers to present the same basic concepts in a context that is personally meaningful and socially relevant (Hickman & Kahle, 1982). For example, Mendel's laws and the chromosome theory can be presented in the more concrete and personal context of human abnormalities, sex linkage and genetic disease. The foreword of one of the biology textbooks states that teachers will find a number of changes [from earlier editions] including "... an increased amount of application material directly relatable to everyday life" (Morgan, 1981a, p. v). The higher proportion of concrete/concrete type analogies may reflect such a trend away from concepts being taught in an abstract context. A greater number of examples and illustrations are probably used in these biology textbooks compared with the chemistry textbooks, and analogies are utilised to explain these concrete, but none-the-less difficult ideas.

Extent of mapping

The frequent use of simple analogies in biology (61%, see Table 1) may be a factor in students' misunderstandings of some biological concepts, as students are required to perform their own mapping between analog and target. Some simple analogies appeared to be incorporated in the text to explain a simple idea; further mapping between the target and analog could be argued to be unnecessary given the constraints of text space. For example, in the simple analogy, "grazers, those animals that predominantly eat grass, have teeth with numerous small ridges, like a file" (Academy of Science, 1990, p. 217), further mapping may be considered unnecessary. Simple analogies also were used for more complex concepts, like the antigen and antibody relationship for which it has been described that "the antibody has regions on it that fit the shape of the antigen. This is like a lock and key mechanism" (Academy of Science, 1991, p. 180). If such analogies are to have impact as pedagogical devices, further mapping is considered desirable.

With other simple analogies, it was unclear whether they were used as a tool to assist readers to assimilate the concept being conveyed or alternatively for their metaphorical surprise element (Duit, 1991). For example, the following analogy is inadequate if intended to convey information about nucleic processes; however, it could simply have been included to serve a metaphoric sense, adding interest to the written text:

> Because there are four different bases in both DNA and RNA, there are four different nucleotides in each type of nucleic acid. These can be thought of as letters in the language of life. (Academy of Science, 1991, p. 26)

There was little evidence of these metaphoric, simple analogies in the chemistry textbooks examined; the language used in biology may be more conducive to their use. There is concern, however, that simple analogies leave great scope for students to arrive at their own conclusions about the science content. Because of the lack of guidance, these conclusions can only be based on students' own interpretation which may not be in accordance with conventional science.

As seen in Table 1, the chemistry textbooks had a higher proportion of fully mapped, enriched and extended analogies than the biology textbooks. Why chemistry analogies tend to be better mapped than biology analogies may relate to the high degree of abstraction of many of the chemical concepts. The authors of these textbooks may have found that more detailed linking between the concrete analog and abstract target was necessary to create the level of visualisation desired for these abstract concepts.

Recommendations

Historically, school textbooks have played a vital role in the teaching and learning of science. The interactions that occur between students and their textbooks, and the involvement of teachers in those interactions, is an area that is the subject of ongoing research (De Jong & Acampo, 1992). In this study we have focused on one strategy that authors employ in textbooks to assist students' comprehension of abstract concepts - the strategy of analogical representation. This study can inform the teaching of science by highlighting various aspects of analogies included in science textbooks and by proposing four related recommendations that will assist teachers. The following recommendations draw upon the findings of this and other studies, with the intention of improving the teaching and learning of biology and chemistry by investigating instructional strategies and clarifying their implementation in the classroom.

Teachers should:

1. Identify how the abstraction of a particular discipline influences the need for alternative representations such as analogies. Where the nature of the science content is abstract, students who struggle to think in abstract terms will require alternative representations to assist visualisation of the conception. We contend that analogies can be successfully utilised in this role.

2. Learn to recognise analogies in textbooks that students use. If students are practised at recognising a piece of text in a book as being analogous, the likelihood that they will effect analogical transfer correctly should be enhanced. If teachers are able to recognise and highlight the presence of analogies in textbooks, this should facilitate student awareness also.

3. Use textbook analogies with students, supplementing the analogy with further embellishment where necessary. This study has identified the considerable number of textbook analogies that are presented without the provision of overt mapping. If teachers are to use these analogies with their students, we recommend that they assist their students by indicating (or inviting their students to indicate) the shared attributes of the analogy and identifying its limitations (Webb, 1985). Further, studies that have investigated authors' intentions with respect to analogy inclusion in textbooks have described the pressure that science textbook authors are under to keep copy space to a minimum (Thiele & Treagust, 1992). For this reason, we recommend that teachers consider neither the frequency nor the limited embellishment of textbook analogies as a guide to the use of analogies in their own teaching. Rather, they should be free to use them when appropriate provided that due caution is given to overt mapping and the stating of limitations.

4. Identify the role that analogical phrases have in language. As has been identified in this study, many scientific concepts are described using phrases that are either overtly analogical or have analogical roots from the historic development or description of the concept. As teachers become increasingly aware of the presence and function of analogical representations in students' learning experiences, and also consider that in some cases the target outcomes of instruction are analogical themselves, they will be able to present teaching episodes to students that will foster more meaningful learning.

Correspondence: Dr David Treagust, Science and Mathematics Education Centre, Curtin University of Technology, GPO Box U1987. Perth, Australia, 6001.
Internet email: itreagus@info.curtin.edu.au

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Webb, M. J. (1985). Analogies and their limitations. *School Science and Mathematics, 85*, 645-650.

Appendix
Textbooks Analysed

Chemistry

Ainley, D., Lazonby, J. N., & Masson, A. J. (1981). *Chemistry in today's world.* London: Bell & Hyman Limited.

Boden, A. (1986). *Chemtext*. Marrickville, NSW: Science Press

Bucat, R. J. (Ed.). (1983). *Elements of chemistry (Vol. 1)*. Canberra: Australian Academy of Science.

Bucat, R. J. (Ed.). (1983). *Elements of chemistry (Vol. 2)*. Canberra: Australian Academy of Science.

Elvins, C., Jones, D., Lukins, N., Miskin, J., Ross, R., & Sanders, R. (1990). *Chemistry in context: Part one*. Melbourne: Heinemann Educational Australia.

Garnett, P. J. (Ed.). (1985). *Foundations of chemistry*. Melbourne: Longman Cheshire Pty Limited.

Hunter, R. J., Simpson, P. G., & Stranks, D. R. (1981). *Chemical science*. Marrickville, NSW: Science Press.

James, M., Derbogosian, M., Bowen, S., & Auteri, S. (1991). *Chemical connections*. Melbourne: The Jacaranda Press.

Lewis, P., & Slade, R. (1981). *A guide to H.S.C. chemistry*. Melbourne: Longman Cheshire Pty Limited.

McTigue, P. T. (Ed.). (1979). *Chemistry - key to the earth.* Melbourne: Melbourne University Press.

Biology

Academy of Science. (1990). *Biology the common threads, part 1.* Canberra: Australian Academy of Science.

Academy of Science. (1991). *Biology the common threads, part 2.* Canberra: Australian Academy of Science.

Morgan, D. (Ed.). (1981a). *Biological science: The web of life, part 1.* Canberra: Australian Academy of Science.

Morgan, D. (Ed.). (1981b). *Biological science: The web of life, part 2.* Canberra: Australian Academy of Science.