Teaching and Learning Science with Analogies

David F. Treagust
Rodney B. Thiele
Allan G. Harrison
Grady J. Venville
Susan M. Stocklmayer

Science and Mathematics Eduction Centre
Curtin University of Technology, GPO Box U1987 Perth 6001

A Symposium presented at the Annual Conference of the Australian Association for
Research in Education. Fremantle, Western Australia, 22-25 November, 1993.

ABSTRACT
Many teachers and textbook writers use analogies to help students understand abstract scientific concepts. However, the teacher or textbook author who chooses to use an analogy to enhance student understanding may differ with the student in the way they visualise the analogy and in the manner they map the analog-target attributes. For this reason, analogies have been called "two-edged swords" and several researchers have highlighted the necessity for educators to identify both the shared and the unshared attributes of each analogy.
This symposium comprises four inter-related studies which provide a critical analysis of the role of analogies in science teaching and learning. The first study focuses on the intentions of textbook writers when they include analogies in the textbooks they write, while the second study evaluates one approach for teaching science concepts with analogies in a systematic manner. The third study describes a newly developed teaching guide for incorporating analogies which is informed by collaborative research with several science teachers in Perth schools. While the findings of these studies are promising, analogical instruction needs further research to detremine whether analogies used inteaching can produce enhanced understanding of the phenomenon. Subsequently, the final paper of the symposium provides an examination and evaluation of analogies used to understand the phenomenon of electricity.

CONTENTS

Chemistry Textbook Authors' Views About Analogies

This study combines a critical analysis of analogies found in chemistry textbooks used by Australian senior high school students with the views of the textbook authors about analogies in chemistry textbooks and teaching. Firstly, eight chemistry textbooks used in Australian senior high school chemistry classrooms were examined to determine the extent and nature of any analogies. Specifically, the study investigated the frequency of types of analogies, compared the frequency of analogy use for particular sections of chemistry content and identified textbook authors' incorporation of instructional strategies that directly assist students in using analogies to aid understanding.

Secondly, interviews conducted with the authors of the eight textbooks solicited their views concerning analogy use and their reasons for inclusion or exclusion of analogies in instructional materials, revealed authors' notions of the need for support for textbook analogies, identified any personal appeal for a model approach to analogy teaching and investigated the changes the author would make to a later edition of their own textbook if they were provided with a more thorough repertoire of trialled, familiar analogies. The two parts of the study are described in an integrated manner, following which conclusions are drawn and implications are described.

Procedure

The textbooks analysed in this study had been identified by State syllabus organisations as those current, generally used textbooks for Australian senior secondary chemistry education. Eight chemistry textbooks (see Appendix) were examined and all analogies identified were photocopied and analysed. A portion of text or a picture was considered to be analogical if it was identified by the textbook author as being analogical and/or was in agreement with the working definition of Glynn, Britton, Semrud-Clikeman, & Muth (1989): "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). An analogy requires the selection of a student world analog to assist in the explanation of the content specific target. The analog and target share attributes that allow for a relationship to be identified. Important in the presentation of a good analogy is some evidence of mapping. This process involves a systematic comparison of the corresponding analog and target attributes so that students are fully aware of which conclusions to draw concerning the target concept being addressed.

Each analogy was scrutinised concerning the following features, four of which (b, c, d and e) were reported for American science textbooks by Curtis and Reigeluth (1984): (a) the content of the target concept; (b) the extent of the mapping done by the author; (c) evidence of further analog explanation; (d) evidence of strategy identification; (e) whether it was verbal or pictorial; and (f) the presence of any stated limitation or warning.

Following this analysis, semi-structured interviews were conducted (Yin, 1988) with seven authors referred to as A, B, C, D, E, F and G - one of whom was the senior editor of two textbooks. Six interviews were conducted in person and lasted between 60 to 80 minutes, while Author E was interviewed via telephone and the conversation tape-recorded with that author's permission. During each interview examples of analogies identified from the author's own textbook were used, wherever possible, to focus discussion and to assist in the clarification of terms used by the interviewer and interviewees. All interviews were tape recorded and transcribed.

Results

The data collected from this investigation have been organised under three major themes: The presence of analogies in chemistry textbooks, analogical characteristics of analogies in chemistry textbooks and chemistry textbooks with an analogical teaching model. Each theme deals with some of the specific research concerns described earlier.

The Presence of Analogies in Chemistry Textbooks

Authors' understanding of analogy? The authors' ideas of what did and did not constitute an analogy indicated general agreement with each other and with the research literature though there was some variation in the discussion. Author C suggested “all science is analogy” due to the use of symbols in instruction and descriptions of invisible processes and entities. Authors D discussed and demonstrated what could be described as a rice analogy for particle theory relating to the states of matter (Knox & George, 1990), though this demonstration could better be described as an “analog model.” The authors did not confuse analogies with examples and were able to clearly identify two discrete domains in the analogies that were discussed although, for several of the authors, there was evidence of a lack of discrimination between “analogy” and “model.”

Analogy frequency of textbooks. The results of the textbook analysis revealed that Authors A, E and G used analogies more frequently (12, 14 and 18 analogies, respectively). Textbooks by the other four authors contained between one and five analogies: B, one; C, four; D, five and three; and F, five. The textbook by Author E contained almost four times as many words as the other textbooks so, on an analogy by word count analysis, it was considered to show a similar frequency of analogy use as the textbooks by Authors B, C, D and F.

Analogically supported chemistry topics. Having established that the frequency of analogy inclusion varied markedly between authors, the researchers wished to determine what role the nature of the content played in the inclusion of analogies. Hence, the content areas of the target concepts that had been supported by the 62 analogies were classified into 15 general chemistry categories. A considerable proportion of the analogies (12, 19%) related to “atomic structure” - including electron arrangement. Other areas in which analogies were used more frequently were found to be “energy” - including collision theory - (9, 15%) and “bonding” (8, 13%). The submicroscopic nature of these target concepts indicate that the analogies may have been included primarily as a tool to aid visualisation.

Characteristics of Analogies in Chemistry Textbooks

Visualisation effect of analogies. Researchers (Glynn et al., 1989, Shapiro, 1985) argue that the visualisation process is very important in the learning of concepts and that analogies prompt a visualisation process that aids understanding. When asked why he decided to include a particular analogy in his text, Author D responded by stating that “we use an analogy that is in our experience, that is ... something we can relate to and can visualise.” Given the importance of the visualisation process, the researchers investigated the format in which analogies were presented in the textbooks. One method to improve the visualisation effect for analogies is to use a pictorial analogy, including some diagrammatic representation of the analog, rather than a verbal analogy. Pictorial analogies comprised 55% of all analogies and were frequently positioned in the margin, possibly as an anecdotal package of helpful information. In contrast, verbal analogies were rarely found in a marginalised position indicating that authors used pictorial analogies more frequently but tended not to sacrifice copy space. Those authors writing texts with marginalised comments tended to make use of the opportunity to use this space for pictorial analogies, though in the interviews, authors acknowledged that publishers requested the cost of the book be kept to a minimum and, hence, copy space was limited. The one exception to this was Author B, who had included a pictorial analogy because one particular chapter of the textbook was lacking visual appeal and the publisher had requested a picture on a particular page.

The extent of mapping. Science education research literature relating to the use of analogies has stressed the importance for teachers and textbook authors to overtly map the shared target and analog attributes (Duit, 1991, Glynn et al., 1989, Webb, 1985). Hence, the researchers classified the 62 analogies to determine the extent of mapping done by the textbook authors using Curtis and Reigeluth’s (1984) criteria of “Level of Enrichment”: (a) simple - states only “target” is like “analog” with no further discussion; (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 textbook analysis showed that the use of simple analogies (23, 37%) was not uncommon although a substantial proportion of the analogies were either enriched (26, 42%) or extended (13, 21%).

When asked about the need for mapping in the textbooks, the authors frequently contrasted textbook analogies to analogies used for classroom teaching. For example, commenting upon a particular simple analogy for chemical equilibrium, Author B remarked that “I wouldn't mind using it myself if I had control of the situation in a classroom situation.” However, he emphasised the lack of control available once the analogy is in textbook form by adding that he “wouldn't like to stick it in a text where everybody is going to use it.” Similarly, Author C responded that he “would be reluctant to use an analogy in a textbook because [he did not] know that you could ever, in words, provide an adequate representation for all students.” Later, he emphasised that when you are teaching you can respond to those students who do not understand the concept by an analogy or further explanation but that “you do not see the blank faces of the students you are writing the text for.”

Author A indicated several analogies in his textbook that he used in his teaching but suggested that they lost something in print because, when used in the classroom, they could be presented to foster interest. He, like the others, indicated that analogy was something of a spontaneous exercise and that he was more likely to use analogies when attempting to explain an abstract idea to students after the students had indicated that they did not clearly understand. For example, Author C commented that “analogy is a very personal thing, something you might deal with on a one-to-one basis.” While acknowledging that he used analogies in his own chemistry teaching, Author F commented upon the need to change or adapt analogies and models to suit the changing circumstances of the lesson and pupils.

Analog explanation. A significant constraint on the use of analogies in teaching is the learner's unfamiliarity with the analog selected by the textbook author or teacher. Several empirical studies on the use of analogical reasoning in chemistry instruction (Gabel & Sherwood, 1980, 1984) indicated that a significant proportion of students did not understand the analog sufficiently well. These results emphasise the need for caution in teaching with this method and in making instructional decisions based on an evaluation of those analogies that are presented to improve student understanding of chemistry concepts. A strategy that can be employed by textbook authors to reduce the problem of analog unfamiliarity is to provide additional analog explanation concerning the analog and its relevant attributes. This will provide useful, additional information to the student. This analog explanation ensures that students focus upon the appropriate attributes at the time they attempt analogical transfer. The explanation may constitute a simple phrase of only a few words through to a paragraph thoroughly describing the analogy attributes.

From the textbook analysis, a majority (43, 69%) of the analogies included some analog explanation and, from the interviews, most authors expected that classroom teachers would engage themselves in explaining the content of textbooks, and hence analogies therein, to their students. Author F described how he taught using analogies directly from the textbook, discussing attributes that the analogs and targets shared as well as discussing the analogical limitations. Author G also was able to describe how she taught directly from the textbook and discussed the analogies with the students in the classroom. This author remarked that, while “it was the teacher’s role to explain” what was in the textbook, the textbook should be sufficient instruction if the teacher was away. Further, Author B indicated that the book should be sufficiently clear for students to work through it themselves without undue difficulty. This could indicate that, while textbook authors expect teachers to provide additional explanation of the analogies, the inclusion of analogies is not presupposed on that additional teacher explanation.

Strategy identification. Students may encounter difficulties when using analogies in textbooks if they do not readily recognise a passage as being analogous. While in a formal classroom setting, an alternative explanation may be distinguished from normal content discussion by changes in the teacher’s voice or manner, this is not so obvious when the analogy is embedded in the text of a book. The use of strategy identification, where the author engages a term such as “analogy” or “analogous,” may serve as a warning to students that careful thought is required to derive the full and correct meaning from the adjacent analogical statement.

Only 15 (24%) of the analogies included any statement clearly identifying the strategy such as “an analogy,” “analog,” or “analogous.” It is likely that if this strategy identification was employed 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 and the students may be less likely to transfer analog attributes incorrectly to the target (Glynn et al., 1989). When asked about the need to identify analogies found in the textbook with some strategy identification, Author F remarked that he did not know if an analogy was described as such in the textbook but that “certainly I would teach it that way... I do not think we put teaching techniques in the textbook.” This author provided evidence of an interesting delineation - that the inclusion of an analogy was a learning technique and suitable for students whereas strategy identification was a teaching technique less suitable for inclusion. An alternative position is that, while cognitive strategies are considered applicable, meta-cognitive strategies are not.

Analogical limitations. When analogies are used during classroom instruction, discussion between teachers and students about the analogy should assist in the delineation of target and analog boundaries and aid concept refinement (Licata, 1988, Thiele & Treagust, 1991, Webb, 1985). Allowing for student involvement and discussion at the classroom level provides feedback to the instructor if incorrect attribute transfer has occurred. Authors and teachers should not assume that students are capable of effecting correct analogical transfer unassisted but rather, they should provide explicit instruction on how to use analogies and provide opportunity for classroom discussion on the subject. The highlighting of unshared attributes may also be done by a textbook author although documented evidence of this occurrence, from a U.S. perspective, is rare (Curtis & Reigeluth, 1984). Textbook authors may assume that this is not required, or that teachers will conduct this aspect with the students in class time. Further research, however, indicates that teachers tend not to expand upon analogies contained in their students' textbooks when conducting their normal teaching routines (Treagust, Duit, Lindauer & Joslin, 1992).

Each of the 62 analogies was examined to see if it included either a general statement of the limitation of analogy use or a statement relating specifically to the unshared attributes in the analogy. No general statements concerning analogy use were made in any of the textbooks and only seven specific warnings or limitations were expressed. However, all authors seemed to be aware of the need for analogies used in the classroom setting to be discussed by both teachers and students.

When the researchers asked the textbook authors about the need to show limitations of an analogy in their textbooks, the authors contrasted textbook analogies to those used in a classroom situation by a teacher. Having described an analogy for a semi-conductor, Author E commented that the analogy had been created spontaneously by him as a result of being questioned concerning the target concept by some students after a class. In this situation, he could “push it [the analogy] to outrageous lengths, then, when they have seen the point you can throw the analogy away and come back to the point you are trying to make.” Author C suggested that when using analogies on the whole class level, that he would build the analogy and then destroy it to illustrate where the analogy broke down. He proposed that the instructional value was in the resulting discussion and evaluation of the unshared attributes rather than in the construction or presentation of the analogy. When questioned concerning a particularly problematic analogy for chemical equilibrium, Author B commented that “maybe the way to deal with it is to point out what is wrong” with the analogy. These findings may add support to the suggestion that authors are either assuming students are capable of effecting the analogical transfer themselves or that the teacher, in the course of normal classroom activities, assists in this regard.

Differences between students and between individual students’ problems with analogies were often commented upon by the authors. For example, Author C acknowledged that, while students’ ability to deal with an analogy should not be overlooked, the need for analogies varied markedly from student to student. He believed that the need is related strongly to academic ability and suggested that “there have got to be some students who will need a little bit more information and there will be other students who will say 'this is pretty tedious stuff'.” In a related discussion, Author D argued for analogies to be placed in the column margin of the textbook “because it is something you could elude to and is maybe useful but it does not interfere with the flow and it is not necessary for the flow and not everyone would need it but it is there if you want to go that way.”

Substantial differences in the knowledge base and cognitive methods of teachers compared to students was identified as a constraint of analogy by Author C. This author had recently conducted his own research study into the teaching and learning of science and he recounted his recollection of a student’s comment about analogy to the effect that:

Analogies are very personal things. What is a good analogy for Mr X is not a good analogy for me because I do not think the same way that Mr X does. It is all right for Mr X - he knows the whole story. I do not. You are trying to present an analogy to me when you know what all of it means. You know what is coming up and you are aware of the history behind that. Here I am, as a student in the first couple of weeks of my senior chemistry course, being thrown into this same thing. I do not know what the end of the story is like. It is like trying to use information that I am going to get in chapters 7, 8 and 9 of my novel to answer a dilemma that I have in chapter 1.

Chemistry Txtbooks with an Analogical Teaching Model

The characteristics of a good chemistry teacher. Each author was asked to briefly describe the characteristics of a good chemistry teacher to ascertain any general leaning towards pedagogical styles that would be particularly conducive or otherwise towards the use of analogies in textbooks. Five authors (B, C, D, E and F), who tended to represent textbooks in which analogies were used less frequently, strongly emphasised that a strong background in chemistry was by far the most important factor. Comments, such as that of Author E, about the requirement for a teacher to be “totally on top of the discipline aspect” and by Author D, of the need for a content knowledge “way in advance of the level you are teaching” as being “the only way that you can have comfortableness, enthusiasm, imaginative ideas, [and] different ways of presenting things,” suggests that these authors

consider that good teaching is based on strong foundations of better content knowledge. Having established this foundation, these authors stated that being interested in students and being able to suitably organise and select the content material were other characteristics of good teaching. For example, having commented upon the need for chemistry teachers to know their subject matter, Author F indicated that “secondly, you have to teach [from] where the students start. You have to know where their knowledge is and what their interests are and start from that basis so that you can build on something.” Authors A and G, who made frequent use of analogies, considered student-teacher relationships as the most important characteristics of good chemistry teaching. Author A stressed the need for the teacher to be interested in the thought processes of students and to “be clear and precise, be fair, and be prepared to admit that you are wrong” while Author G proposed that “it is really most important

Awareness and appeal of a model approach to analogy inclusion. The researchers wished to ascertain if any of the authors recognised Glynn’s (1991) Teaching-With-Analogies model (see Figure 1) or were aware of any models relating to analogy presentation in textbooks and were asked to comment upon their perception of the usefulness of such a model for textbook presentation of analogies after they studied it for several minutes. None of the authors recalled ever having seen or used a model for analogy presentation. Author E was content with the model as it was presented and indicated that it was common sense and that “most experienced teachers would do that without even being conscious that they were doing those things.” The other authors did appear to accept the model as useful although most suggested variations and alterations, or remarked that the best approach varied depending upon the analogy and the setting. The problem of extra length to a textbook was raised by Author F who proposed that analogies using this model approach could be better placed in a teachers' guide than in a textbook. Author G cautioned that, while there was nothing wrong with the model, she would “never like to see a recipe for how you teach.”

1. Introduce target
2. Cue retrieval of analog
3. Identify relevant features of target and analog
4. Map similarities
5. Draw conclusions about target

6. Indicate where the analogy breaks down

Figure 1. Glynn's (1991) Teaching-With-Analogies (TWA) model

Other comments came from Author B who suggested that the "limitations" stage of the model could be presented at the same time as the similarities - that is, before the conclusions are drawn. Author D attempted to clarify a conflict that he felt arose over the use of an analogy that is used to draw conclusions rather than to confirm a previously arrived at conclusion; he remarked that "there certainly must be cases where the conclusion has already been made and, in an attempt to make sense of that conclusion, you might use the analogy." The authors' comments indicate a general acceptance of the model approach for analogy presentation provided that due regard be given for flexibility in various instructional settings.

Proposed future use of a bank of trialled analogies. When asked if they would be interested in incorporating some of a bank of trialled analogies in a fictitious new edition of their textbooks, several of the authors indicated some reluctance. Author C clearly stated that he "would not use them in the textbook," while Author B only agreed to the inclusion on the proviso that the "person writing the book felt comfortable." Similarly, Author E indicated that he would consider them but he would "need a fair bit of convincing that an analogy was a valid one." Authors of the more recent textbooks (F and G), indicated little willingness to deviate from their current analogy use. On further questioning, however, four authors showed particular interest in having these trialled analogies available in the form of a teachers' guide. Author E showed enthusiasm for the idea while Author D proposed that each analogy "could have a [comment] on each of the six steps" of the TWA model. In addition, while Author C suggested that he "might be interested in putting them in a teachers' guide," he qualified his concession by proposing that even in a teachers' guide there would need to be some form of instruction to teachers clearly stating that "you do not just take these into the classroom cold and assume that all your students, at the end, will be enlightened." Alternatively, Author F suggested that although you could embed these analogies into another chemistry book, there could be demand for a "book of analogies ... related to a number of chemical concepts that are pretty universal."

Discussion

Authors who view the foundation of good chemistry teaching to be an excellent understanding of the content tended to use analogies less frequently in their textbooks than authors who believed that teacher-student relationships were the key to good teaching. There are several possible interpretations of this finding. One is that, if knowledge of chemistry is viewed as paramount to teaching, then the communication of the chemistry requires only the content in textbooks and not the inclusion of what one author referred to as “teaching strategies.” An alternative perspective is that those authors who view teacher-student relationships and communication as the foundation for good chemistry teaching include the analogies from their own teaching experience and possibly knowledge of the research literature to address students' alternative conceptions. In addition those authors may use analogies to teach chemistry concepts for which students traditionally require alternative explanations. The authors made frequent reference to analogies used in their own teaching of chemistry though there was a reluctance to include analogies in written materials. These observations suggest that the frequency of analogy inclusion in textbooks is not representative of an author's perception of the usefulness of an analogy to teach chemistry. A later study (Thiele & Treagust, 1993) has revealed that author C, who used analogies sparingly in his textbook and expressed strong views against analogy inclusion in textbooks, used enriched and extended analogies when teaching chemistry.

An analysis of the chemistry topics supported by analogies has emphasised the role that analogies play in improving further visualisation. Atomic structure is considered a key concept by chemical educators - so much so that chemistry textbooks have historically introduced atomic structure in the first few chapters. In some recent textbooks, however, atomic structure topics have been presented after some initial application of chemistry which may be an acknowledgment of the conceptual difficulty of the topic. Similarly to the topics of energy and bonding, atomic structure is an invisible and abstract notion requiring alternative explanations, especially for students who readily do not think in abstract terms. Further, chemistry instruction at the senior level tends to emphasise both the structure of the atoms in terms of the position of subatomic particles in relation to each other and the function of an atom with special emphasis on electronic behaviour. Subsequently, alternative explorations may be essential especially if this key chemistry concept is to be successfully used as a foundation for later conceptual understanding.

With the advent of new instrumentation, such as the scanning, tunnelling electron microscope, chemistry textbooks may show 'pictures' of atoms and molecules. However, for the present time the issue of visualisation of abstract chemistry concept

continues to be problematic for many students of chemistry. Hence pictorial analogies have been frequently engaged by the authors of the textbooks to aid students creation of mental pictures about these abstract concepts. One of the difficulties with this visualisation is that students can over-internalise the analogy (such as the Bohr orbits), making the conceptual development to a higher chemical concept (e.g., the orbital) difficult. Research continues to address these issues in other topics such as electricity (Stocklmayer & Treagust, 1993).

A relatively high proportion of analogies included some further mapping of analog and target attributes, although there was evidence that some authors who used analogies more frequently were less inclined to include mapping. A possible interpretation of these findings is that authors who know the difficulties that students have in correctly effecting analogical transfer, tend either to map them explicitly or leave them out entirely, although the findings of this study are not conclusive in this respect.

The authors did appear willing to use analogy in an informal manner in their classroom setting and often referred to the types of interactions that both teachers and students could have with an analogy. The researchers believe that this willingness to negotiate an analogy, to “push it to outrageous lengths,” “point out what is wrong” with it, “have control over it,” and to “destroy it to illustrate where the analogy broke down” augers well for the continued use of analogies in the classroom. A related aspect of this is the authors' support for analogy use as a response to a perceived difficulty rather than as a pre-planned cognitive strategy. Various comments about analogy being “a very personal thing” and “something you might deal with on a one-to-one basis” add support to the stated difficulty of trying to respond to an anticipated need when you are unable to “see the blank faces of the students you are writing the text for.” The authors did not generally consider that analogies could effectively cater for the wide ability range of the readership when they were set in a textual situation.

The infrequent inclusion of strategy identification and/or analogical limitations did not surprise the researchers as the findings reflected those in a similar study (Curtis & Reigeluth, 1984). Implicit in the responses of the authors to questions related to these aids to analogical understanding was the notion that meta-cognitive strategies did not belong in a textbook written for 16 year olds. In addition, it was felt that the classroom teacher would add support where necessary. Unfortunately, not only is it not well known whether and how teachers use chemistry textbooks to aid their students' conceptual understandings (De Jong & Acampo, 1992), it is unlikely that students will be immediately aware when they have incorrectly mapped the analog attributes.

The authors' varied perspectives of the model approach proposed by Glynn (1991) added further to the notion that they saw teaching with analogies as being substantially different to including analogies in textbooks. While it was acknowledged that steps similar to those in the TWA model were appropriate for good analogically-inclusive instruction, there was resistance to teachers being given “a recipe for how you teach” - the authors making it clear that full flexibility was a chief requirement. There was resistance to the use of a similar model for analogies in textbooks due to the extra copy length required, but several authors recommended including such strategies in a teachers' guide which could describe the analogy and its most efficient use and the choice as to if, when and how to use it.

Based on the author interviews it is unlikely that there would be an increased frequency of analogies included in new textbook editions. However, there was support for trialled analogies to be added into teachers' guides as well the

publication of a book of analogies which teachers could use to enhance their own repertoire of analogies. Teachers with a good repertoire of alternative explanations provides opportunity for better learning to take place (Treagust, in press).

Implications

Research into how students and teachers use analogies in the learning/teaching enterprise indicates that enriched analogies, rather than simple analogies for all but the most elementary relationships, increase the effectiveness of analogical transfer and hence, the understanding of the target domain (Duit, 1991). 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 when these features are included (Glynn et al., 1989). In the analysis of eight textbooks reported in this study and the interviews with the authors, both these issues would appear to require greater attention in order to optimise learning of concepts by analogy use. The authors of the textbooks have assumed that the classroom teacher will use the analogies in such a manner to enhance their pedagogical use. There is a lack of research evidence, however, to support this suggestion since teachers' pedagogical content knowledge is known not to be generally extensive in this regard (Shulman, 1986, Treagust et al., 1992, 1992). Furthermore, the interviews with the authors provided no recommendations of what teachers were expected to do with the analogies and, with the exception of two textbooks, teachers' guides were not written for the textbooks.

Duit (1991) described analogies as double-edged swords and the chemistry textbook authors would in many instances identify with this perception. However, the inclusion of analogies in the textbooks written by these authors reflects variations in the authors' perceptions of the advantages and disadvantages of analogy use as well as reflecting variations in their respective teaching backgrounds. The frequency of analogy inclusion in the textbooks does not seem to be indicative of the willingness of the authors to use analogy in their own teaching; rather they are unwilling to set the analogy to print because of their belief that teaching with analogies should involve discussion or negotiation with the students. This is not possible in a textbook situation.

The unfamiliarity of the authors with research guides regarding analogy presentation highlights the problems of the efficient dissemination of research findings in science education to practitioners. However, the willingness of the authors to accept a model approach to analogy teaching, albeit a more flexible one, indicates the usefulness of such an approach. Also, it should be considered that there is still a lack of empirical research findings suggesting that analogy presented in the model format aids student understanding more than analogies presented in other ways.

As we observe chemistry teachers and their students in regular classroom settings using analogies to better understand complex concepts, we anticipate that we will be able to determine for whom and under what conditions analogies are most beneficial in secondary school chemistry. Subsequently, we plan to provide materials, in the form of a teachers' guide, which is consistent with the recommendations of the textbook authors and which will enable analogies to be used by chemistry teachers and their students in an exemplary fashion.

Developing Teacher Expertise in the Use of a Systematic Model for Teaching Analogies in Science

This section documents part of a collaborative enterprise in which the researchers worked with an exemplary teacher over a period of three months trialling a systematic model for teaching with analogies in science. Analogies are powerful and popular tools of communication but their value in the classroom is open to question. Both Duit (1991) and Glynn (1989) describe analogies as "two-edged swords" and this encouraged Treagust, Thiele and Venville (1991) to search for a systematic model for analogical teaching that could enhance student learning. Of the available models (Brown & Clement, 1989; Dupin & Johsua, 1989; Glynn, 1989, 1991 and Zeitoun, 1984) Glynn's Teaching-With-Analogies (TWA) model was believed to be the most facile for teacher use, thus Glynn's TWA model was modified to produce the systematic approach used in this research.

With little empirical evidence available regarding teachers' use of analogies (Treagust, et al., 1992), a need existed to examine in depth whether the chosen model could systematise teacher presentation of analogies and thus enhance student understanding of scientific concepts during analogical instruction. Six teachers who were supportive of classroom research and who were desirous of improving their own practice indicated their willingness to trial the modified TWA model. Throughout the trials, one of the researchers worked closely with each teacher in a collaborative partnership.

A Systematic Approach for Teaching With Analogies

While an analogy can be useful to identify weaknesses in a student's understanding, the analogy itself must be used economically and in a valid and reliable way. An analogy enables valid concepts from a familiar domain to be used to challenge the student's alternative conceptions with the result that the learner may be stimulated to reconstruct his or her knowledge (Sutula & Krajcik, 1988). Evaluation of a systematic model for analogical instruction can highlight the dangers inherent in the haphazard, uncritical use of analogies in the science classroom and may provide science teachers with an efficient model for improving their teaching.

Consequently, this study evaluated the efficacy of the modified Teaching-With-Analogies (TWA) model in secondary physical science classes spanning grades 8 to 10 with 13-15 year old students. The systematic approach for teaching with analogies used in the study was derived from Glynn's six step TWA model (1989) and can be summarised as:

1. Introduce the target concept to be learned.
2. Cue the students' memory of the analogous situation.
3. Identify the relevant features of the analog.
4. Map the similarities between the analog and the target concepts.
5. Identify the comparisons for which the analogy breaks down.
6. Draw conclusions about the target concepts.

Glynn's TWA model (1989) had steps 5 and 6 above, reversed. However, early trials of Glynn's model showed that teachers tended to introduce the shared and unshared attributes side-by-side resulting in their adjacent positions in the modified TWA model. It was reasoned that if the conclusions of Step 5 were drawn before the unshared attributes were identified, then alternative student conceptions would arise more often than when these invalid comparisons were identified before the concluding summary. Subsequently, the aim of the research was to evaluate how well this systematic approach to analogical instruction could be implemented to enhance and/or develop teacher expertise.

Method

Because analogies are devices of human communication, it is important to determine the analogy's meaning for the teacher and the students and for this reason the study employed classroom observations and audio-taped recordings in combination with teacher and student interviews. Each episode was transcribed verbatim and analysed to yield data for interpretive analysis. Consequently, the research mode was that of a qualitative case study which also used some quantitative data (Merriam, 1988). The emphasis throughout the study was upon producing constructivist interpretations that were trustworthy, credible, transferable and dependable (Guba & Lincoln, 1989). Put another way, the aim was for outcomes that were plausible, viable and that possessed face validity (Patton, 1990).

In our research project we worked with six science teachers; in total 12 different analogies were taught using the modified TWA model. Four analogies used by one teacher, who will be called Mrs Kay, are reported in Harrison (1992). Mrs Kay derived the wave nature of light from water wave characteristics, conduction of heat through a solid was likened to the domino effect, the slowing of light and its refraction as it passes from air into glass was demonstrated using a pair of wheels rolling from a hard surface onto a soft surface and the mole concept was taught using three short analogies in which the particles of a mole were likened to dollars, oranges and rice grains. For this section, one lesson from this subset is discussed.

The criterion employed for school and teacher selection was "purposeful sampling" in which Patton (1990) points out that "[t]he logic and power of purposeful sampling lies in selecting information-rich cases for study in depth" (p. 169). Mrs Kay was "purposefully" chosen because she is an experienced physical science teacher, is highly regarded in her school as an innovative teacher, often uses analogies, was cooperative and was teaching in-field. The Year 10 class that was studied consisted of 29 average ability girls attending a private school and the interview subjects were chosen on the basis of the extent of their responses on a post-lesson worksheet. Thus, this study does not claim to be fully representative of the local educational environment and for this reason the constructivist notions of rigour are particularly useful for case studies of this type.

Throughout this study, Mrs Kay maintained full control over the teaching agenda; she made the decision to use an analogy, chose the analogy and set the time for its implementation. Initial in-service information consisted of providing Mrs Kay with a two page description of the modified TWA model along with a discussion of the advantages of systematic presentation of analogies. This occurred several days before the lesson in which the first analogy was to be used and was followed up with a review of the model on the day of the lesson. A post-lesson discussion provided an opportunity for Mrs Kay and the researchers to reflect upon the lesson just completed and to prepare for the next implementation of the model. Subsequent lessons were preceded by a review of the modified TWA model and concluded with a reflective interview.

For the third lesson which is the subject of this section, Mrs Kay's Year 10 class was studying the topic Light. The written objective for this lesson was: "Draw ray diagrams to show what happens when light enters glass along a normal or obliquely to a normal." Mrs Kay decided to use the wheels analogy to model refraction of light and presented this analogy within the modified TWA model framework. The lesson itself was audiotaped as were both the post-lesson teacher interview and the subsequent student interviews. Each student who heard the analogy completed an analogy mapping worksheet at the commencement of the lesson immediately following the presentation of the analogy (Olivera & Cachupuz, 1992). This worksheet examined both the shared and the unshared attributes of the refraction analogy and these responses were then used to select the subjects for interview. Students were interviewed if they had completed all or most of the attribute matches on the worksheet irrespective of whether those responses were correct or not. The selection criterion was again "purposeful sampling" reasoning that students who provided lengthy written comments were likely to be productive during

interview.

An Analogy to Represent the Refraction of Light

Students are familiar with the fact that light bends when it passes from one transparent substance into another and even though refraction is easy to demonstrate in the classroom, the usual explanation is both abstract and conceptually demanding for many students. With this in mind, Mrs Kay decided to analogically demonstrate refraction by rolling a pair of Lego®wheels coated with paint obliquely from a smooth surface (paper) onto a rough surface (carpet) as illustrated in Figure 1. When the wheels rolled from the paper onto the carpet so that both wheels crossed the interface simultaneously (angle of incidence = 0o) no bending occurred, but when the wheels crossed the interface obliquely (angle of incidence = about 30o) the wheels changed direction in a manner comparable to the refraction of a light ray passing obliquely from air into glass.

Figure 1: Refraction of light as it passes from air into glass is like a pair of wheels slowing down as it rolls obliquely from paper onto carpet.

The lesson notes and the lesson transcript were analysed for evidence of the six steps of the modified TWA model and each of the six steps is discussed sequentially under its relevant heading.

1. Introduce the Target Concept to be Learned

Refraction of light was introduced by showing the students that a ray of light changes direction when it passes from air into glass. The demonstration using a glass block (Figure 1) precipitated the question, why do light rays bend when they pass obliquely from one transparent medium into another?

2. Cue hte Students' Memory to the Analogous Situation

Because many of the students would not have had direct experience of the analog, it was established by demonstration using the apparatus illustrated in Figure 1. Being simple and visual, the analog became familiar to the students as it would remind many of them of Lego® wheels. This led Mrs Kay to state the analogy:

Let me show you a little analogy to illustrate this. This is what all the paint's for, now to represent the ray of light, I'm going to use this pair of wheels here coated in this nice fluoro paint (Figure 1) ... this is meant to represent the ray of light. I'm going to use this pair of wheels here coated in this nice fluoro paint. Now I'm going to do two demonstrations ... our

wheels going forward are meant to represent the ray [of light].

3. Identify the Relevant Features of the Analog

On the two previous occasions that Mrs Kay used the modified TWA model, she employed the six steps in a simple sequential manner. This third instance suggested that she was more confident in the use of the model because she altered the order of the steps to suit her explanation and the class' needs. The feature of the analog that was most important at this juncture was:

[the wheels are] really like the two edges of the ray of light as it starts off ... it's wider and it's deliberately wider because it's a little bit hard to see the reason for its bending when it's as narrow as this (points to light ray). When it's wider it's a little bit easier to see the reason [for bending]

The wheels were rolled from the paper onto the carpet twice; once at an angle of incidence of 0o and then at an angle of incidence of about 30o.

4. Map the Similarities Between the Analog and the Target Concepts

In explaining refraction of light by comparing it to wheels that slow down as they roll from a smooth surface onto a rough surface, Mrs Kay utilised six propositions as the shared attributes of the analogy: (a) the two wheels represent the edges of a the light ray; (b) a ray that strikes the glass at 90o is not bent; (c) a ray which strikes the glass at an angle is bent; (d) the ray bends because it slows down; (e) when the ray strikes the glass at an angle, it bends towards the normal; and (f) the light slows down because the glass is denser than air. Nine students were interviewed on the day after the lesson immediately following the completion of the worksheet and these students' relevant responses to the above six propositions follow.

(a) The two wheels represent the edges of a the light ray. This proposition was introduced when Mrs Kay said that "[the wheels are] really like the two edges of the ray of light." On the worksheets, only 10 of the 29 students actually recalled this proposition in its correct form. Nineteen students responded saying that each wheel is like a ray of light. This response may be a simplification rather than an error of understanding because all but one of the nine girls interviewed talked about the wheels being analogous to the edge of the ray. Matching named worksheets to the interviews, four girls wrote that each wheel was like a ray of light but then talked about the wheels representing the edges or sides of the ray of light. One girl, Cath, both wrote and said that the wheels represented separate light rays. Other student comments were typified by Jane's comment, "... one side of the light as shown in the wheel example

(b) A ray that strikes the glass at 90o is not bent. This propositional statement was derived from Mrs Kay's comments, [The wheels are] like the ray of light going through the block along the normal ... just push it straight. Both [wheels] slow down at the same time so that they both would be moving slower, but it doesn't change direction. It's the same with a light ray, if the light ray goes through at right angles, it slows down but it doesn't change direction.

Each girl explained during her interview that when the light ray struck the new medium at right angles (parallel to the normal) it did not bend. Most could explain this in terms of both sides of the ray slowing down simultaneously. In response to the question "Does a ray of light always change its direction when it passes from one transparent medium into another one?", Jane stated ... "not if it enters it at right angles into the medium ... it doesn't change direction." Similarly, Kay responded "... no it doesn't if the light ray was on the normal because if they hit the medium at the same time, ... travelling perpendicular, then it wouldn't bend because they both slow down at the same time."

(c) A ray of light that strikes the glass at an angle is bent. Discussion during the lesson about the wheels crossing the paper/carpet joint obliquely highlighted this propositional statement.

Mrs Kay: ... it has bent and that light did more or less the same thing didn't it? When we passed the light through our block at an angle, light also bent. Why does it bend when it approaches like that?

Sally: When the wheel is on a smooth surface it's going faster

Mrs Kay: It's to do with speed. That's exactly the point I wanted to make ... its speed. When we move it here, which wheel is going to slow down first?

Fiona: The one on the carpet.

Mrs Kay: That's right, the one going onto the carpet. It's going to slow down first because there's more friction on the rough surface. Now if you can think of this ray of light as being not quite as thin as it looks, but being wider, do you think, if it was magnified, one edge of the light would hit the block before the other side?

Beth: Yes, yes ...

Mrs Kay: In exactly the same way with light, one edge of the ray slowed down slightly before the other, so this wheel that hits the carpet first, is slowing down first, so that's covering less distance for a time, and obviously, once this one hits the carpet as well, they then become parallel again... so it bends because the wheels and the light ray travel more slowly in a dense medium, or in this case, on a rougher medium.

As for proposition (b), each student interviewed provided an intelligible response indicating that she knew that a ray striking the new medium at an angle would bend. Two of the nine stated that the ray bent away from the normal, though this was reversed later in the interview by Kay who said

, I mean the wheels, and then seeing the light do it you could see how it worked, it was easier to understand.

Similarly, Cath stated that "... the part of the ray that goes in first, that's going slower than the other half so it changes direction."

(d) The ray of light bends because it slows down. This propositional statement, based on the final comment Mrs Kay made in the account reproduced in (c) above, was identified in eight of the nine student interview transcripts. Jen's statement was typical of the overall group when she said,

Because one edge or side of the light beam hits the different medium before the other, so it slows down and the other one keeps going so it sort of bends until the other one catches up and they're both travelling on the same medium. ... One wheel hits the carpet at, before the other wheel just like one edge of the light hits before the other edge of the light.

(e) When the ray strikes the glass at an angle, the ray bends towards the normal. This propositional statement arose following Mrs Kay's question, "...which way will the light bend? Is it bent towards the normal?" to which Emma replied, "It goes towards it." Mrs Kay continued probing - "It's bent towards the normal isn't it? Just look at the light rays and tell me if that does the same thing, does the light ray also bend towards the normal? Dani responded, "Mmm ...Yes." As already indicated, eight of the nine girls stated that the ray was bent towards the normal when light passed from a less dense to a more dense medium. When the interviewer asked, "From a less dense, like air, to a more dense medium like glass, which way will it bend? Jen, Sue and Cath all replied with, "towards the normal."

(f) The light slows down because the glass is denser than air. On this occasion, Mrs Kay asked the class "Why is light bent when it travels from one transparent medium to another?" after which she stated "...it's to do with speed. So we can say

that light travels more slowly in a denser medium." This proposition that refraction was a consequence of changing the speed of the light was mentioned by the girls in each interview. The demonstration of the wheels slowing down going from paper to carpet, coupled with the 'car wheels in the gravel' analogy, made this idea intelligible to most of the students as is illustrated by Jane's comment:

The following shared attribute was identified by the students even though it was not stated by Mrs Kay.

(g) When a ray of light passes from a more dense to a less dense medium, it is bent away from the normal. Six girls were asked this question because it involved extrapolating from the concept and would thus be an indicator of whether or not the students understood refraction following the use of the analogy. However, the students may have just guessed, by saying the opposite to the previous case, but an ability to explain why would favour extrapolation over guessing. In responding to the question "when light passes from a dense to a less dense medium, which way will it bend?", Jane and Sue simply stated that the ray would bend away from the normal but Kay explained it this way - Away from, the normal, because it is, um, the same idea, but the other one comes out from the denser medium first , so it goes faster before the other one catches up, and then it goes on parallel to the other side ... it's the other side that gets there first because it's on an ... angle and it bends back or goes back on the parallel of the ray it started on, before it got into the dense area.

Due to limitations in the interviews, three girls were not asked this question, but all who were asked, gave an answer similar to those above. In four of the six cases the students adequately explained why the ray bends away from the normal using the same arguments as Kay.

5. Identify the Comparisons for which the Analogy Breaks Down

Mrs Kay identified several differences between the wheels and light rays during the lesson. These unshared attributes were:

(a) The pair of wheels were considerably wider than the light ray. The central comment that highlighted this unshared attribute was:

Obviously [the wheels are] larger ... this is really like the two edges of the ray of light as it starts off ... it's wider and it's deliberately wider ... when it's wider it's a little bit easier to see the reason for [its bending].

This issue was examined during the student interviews and resulted in Kay's response to the question, "... but the two wheels were much wider than the ray of light?"

No, no, I don't think that would really matter if I think the wheels were skinny and there were two wheels joined by an axle, it would still go the same. ... It was like similar, but you still had your doubts that your light would be different until she said this is like a version of the light ray. ... If she just got out the wheels and said this is a light ray, I would have questioned that.

(b) There were two wheels but there was only one ray. This unshared attribute was recognised by all the students who were interviewed, the following exchange being typical:

Int: The two wheels were joined together with an axle, are the light rays in a beam joined together like that?

Kay: No they are individual, but they're very close together.

Int: Are the light rays in a beam joined together [like the wheels]?

Cath: ... I wouldn't say they were joined together, I'd more say they're all going in the same direction, do you know what I mean? They're not joined together by an axle so that they can diverge if they wanted to.

Two more unshared attributes not identified by Mrs Kay were identified by the students during the interviews.

(a) Friction slowing the wheels is like friction slowing the light. During the lesson, friction was given as the reason why the wheels slowed down. A minority of the students interviewed recognised this as an unshared attribute. It is apparent though, that many of the students transferred friction as an explanation for the slowing down of light in denser media.

For many, this was probably a misconception. In response to the question, "do you think there's friction between the light and the glass?" four students answered in the affirmative and two of their responses were:

Jane: I don't think there is friction between light and air ... I think there would be between light and glass.

Jan: If the medium's different, because of friction, it's a denser medium, then it's friction.

(b) The two wheels being joined is like light rays being joined. Of the 29 students who filled in the worksheet, 24 recognised this unshared attribute. This level of response may be a function of the fact that this was one of the two invalid mappings where half the statement was provided for the students. The response rate for this semi-complete proposition was far higher than for all but one other partial statement. That nearly all members of the class recognised this link as invalid is indicative of the usefulness of this teaching method.

One misconception emerged during the student interviews. Sue revealed that she thought the ray bent towards the normal because this provided a shorter route through the glass block. If the ray slowed down, it took a more direct (shorter) route. She was the only student who held this idea and in response to the question, "can you link the slowing down with the reason why it bends?" she replied, "Um, it is easier, to make the path shorter to get though the block."

6. Summarising by Drawing Conclusions About the Target Concept

The ideas derived from the analogy were then transformed by Mrs Kay into a summary that provided the students with a statement of the concept of refraction of light. "At all angles, [light] slows down ... if it enters another denser medium. If it enters at an angle, it changes direction." The probable value of this steps rests in the identification and integration of the key ideas derived from the analogy into a conception that was intelligible, plausible and fruitful for these students.

Discussion of this Teaching Approach

Throughout this lesson, the systematic approach for incorporating analogies into teaching using the modified TWA model was subsumed into the lesson with each stage being used when and wherever Mrs Kay felt it was instructionally necessary. The lesson commenced with Step 1 and concluded with Step 6, but Step 2 (cuing the students' memory to the analogy) occurred three times, Steps 3 and 4 occurred twice and Step 5 (the unshared features) was similarly treated on two occasions. The effect, both at the time of the lesson and in rereading the transcript, was to characterise this lesson as being systematic while preserving spontaneity.

This integration of the modified TWA model into the fabric of the lesson is illustrative of the expertise developed by this teacher in using the model for incorporating analogies into her teaching. To say that she was delighted with the lesson's outcome is evident from her comments and the manner in which she expressed them.

I thought that was the best I've ever taught that ... refraction from the point of the students understanding it. They seemed to just say, Oh yea, no worries, at the end, and that's what I like about it. ... It's certainly something I'd certainly do again.

Credence has been ascribed to an experienced teacher's qualitative assessment of the lesson's effectiveness in respect to student cognition. Mrs Kay gave her assessment of the analogy's effect during the post-lesson interview when she said:

I was really pleased with [the analogy] actually, [refraction] was something I've always found hard to explain, and I don't know that the kids find it easy, but I thought, doing it that way, clarified it a lot. ... I felt at the end of the lesson they seemed to have a good understanding of it. Something I noticed was that sheet that I gave them at the end of the lesson, I said does it bend towards or away from the normal, they had no problem with that today. ... They all seemed to say towards it, where normally they will say, what on earth do you mean ... they seemed to have a better understanding than usual, I felt. I was really happy with it.

The analysis of the student interviews at Step 4, mapping of the similarities between the analog and the target, supports this assertion. Not only did eight out of the nine students interviewed consistently predict that the light would bend towards the normal when passing from a less dense to a more dense medium, they also provided a cogent explanation for this phenomenon based on the observed analogy. Moreover, when they were asked to extrapolate in stating which way the ray would bend passing from a more dense to a less dense medium, the majority unhesitatingly stated "away from the normal" and again could explain why. In giving these explanations, the students moved freely between the wheels analog and the light target. At this stage it is asserted that the students found the analogy useful as an explanatory tool and as a means of articulating their understanding.

During unrecorded conversation following the interview, Mrs Kay expressed her delight at the consistent manner with which the students could predict the direction of bending. A look back at the lesson transcript shows that Gemma, at the point where the wheels changed direction, spontaneously exclaimed, "Isn't that because the wheels will move faster on the [paper]", to which Mrs Kay replied "Yes. Exactly, yes ..." From the students' viewpoint, it was evident that they believed that the analogy helped them understand refraction. Two responses support this assertion:

Kay: I think it was helpful because you could actually see the tracks of paint from the wheels ... it was helpful to understand the light rays bending. But you just have to know what are different and that.

Cath: It wouldn't have been easy to understand if she had just put it on the board in a diagram, it just wouldn't have gone in, do you know what I mean ... by demonstrating it, it actually registers, but otherwise it probably wouldn't have. ... it was a good way of explaining ...

By the third episode, Mrs Kay had developed a high level of expertise in the use of this model and it was observed that the model had become subservient to her's and the students' needs. Interviews with a sample of the students from each class focussed upon each student's understanding of the concepts presented via the analogy. When the student worksheet and interview data were combined with Mrs Kay's personal perceptions of the students' understanding of refraction, it was concluded that the students' conceptual understanding was compatible with the expectations of the teacher and comparable with what was expected at this level of schooling.

The fruitfulness of the students' extrapolations and their curiosity suggests that some students were willing to reconstruct their prior conceptions. Nevertheless, without pre-lesson interview or survey data to define individual student's prior conceptual status, such conclusions must be limited to saying that there was credible and dependable evidence of an acceptable understanding of refraction shown by the students interviewed.

Conclusion

Based on the data collected over four lessons, the third one of which has been described in detail, it is asserted that in this instance, with this teacher, a systematic approach like the modified TWA model appears to be an achievable means for developing expertise effectively to use analogies in the science classroom. However, even with an experienced and competent teacher, the implementation of the modified TWA model requires both practice and collegial support in the form of constructive feedback (Wallace & Louden, in press). Whether or not this finding is transferable to other teachers, times and places has yet to be determined.

Previous research by Joyce and Showers (1983) that describes the collaborative process by which teachers integrate new pedagogical models into their repertoires suggests that up to 12 trials over several months may be required to fully integrate an unfamiliar methodology. These authors reinforce the need for collaboration by saying that "[c]ontinuous practice, feedback, and the companionship of coaches is essential to enable even highly motivated persons to bring additions to their repertoire under effective control" (p. 4). Joyce and Showers indicate that four essential elements of this integration process are: (a) study of the rationale and theory of the new method; (b) observation of expert demonstrations; (c) practice and feedback in nonthreatening conditions; and (d) coaching, companionship and opportunity for reflection.

Based on our studies with Mrs Kay and five other teachers, it is likely that the majority of practicing teachers would require extended practice combined with critical feedback before they could master the modified TWA model for presenting analogies in their lessons. Three applications of the model may be a minimum number of trials in order to achieve limited expertise with the modified model for analogy teaching. Additionally, research involving teaching innovations suggests that teachers will probably adapt the model to suit their personal teaching style.

The FAR Guide for Teaching and Learning Science with Analogies

It is frustrating after spending much time and patience teaching a scientific concept with simple, careful language, to glance up and see a look of perplexity on students' faces. One possible avenue of action is to explain the scientific concept in terms of an analogy. This section of this paper discusses a teaching approach designed to make the option of analogy as a tool of explanation a viable and valid one for science teachers.

In a narrow sense analogies are stated between four terms: x:x'::y:y'. In this form analogies are used in tests where a person is required to judge an analogy true or false, or to determine an appropriate value for the fourth term (Miller, 1979). A simple example of this kind of analogy is: Toe is to foot as finger is to hand. Here we will be investigating the use of analogies as a tool of explanation and therefore a broader definition of analogy will be used. An analogy in this regard is the process of comparing features of two concepts. When analogies are used for the purpose of explanation one of the concepts is familiar and the other one is completely or partly unknown. For example the double helix structure of DNA, the molecules which make up chromosomes, is often described as being like a ladder which has been twisted into a spiral. The familiar concept (the ladder) is referred to as the analog and the unknown concept, (the DNA) is termed the target. The features of the two concepts that are compared are called the analogous attributes and the features which are dissimilar are referred to as unshared attributes or limitations. In this terminology we follow Duit (1991) and Glynn (1991).

Why might analogies be successful in helping the students learn something new when clear and simple explanations of the "real science" don't work? Learning can be thought of as a process of making sense of experience which involves the reflection on prior knowledge (Tobin, 1990). If new information is presented in a way that is difficult for students to relate to their prior knowledge, then it would seem that learning will be inhibited and less likely to occur. By using analogies a teacher is guiding the process where new information is integrated with the students' prior knowledge. Analogies, however, have the capacity to facilitate desirable and undesirable cognitive development. It is therefore imperative that teachers who use analogies to teach science do so in a manner which results in desirable outcomes in terms of their students' cognitive development.

Duit (1991), gives an overview of the advantages and constraints of analogies as seen from a constructivist position. He says that analogies can be useful pedagogical tools in that they are thought to help students construct new knowledge by linking it with knowledge structures they already have. Additionally analogies have also been shown to be valuable when trying to help students to visualise abstract or unobservable phenomenon. A third and sometimes overlooked advantage of teaching with analogies which Duit mentions is the motivational role they can play in the classroom. If the teacher uses an analogy which draws upon the students' real world experience, a sense of intrinsic interest can be generated. If students are able to achieve a higher level of conceptual understanding than usual because of the analogy, this also can result in motivational gain. Much empirical research has found that analogies can contribute to improved understanding of scientific concepts. (Bean, Searles, Singer & Cowen, 1990; Dupin & Johsua, 1989; Gentner & Gentner, 1983; Shapiro, 1985). Treagust, Harrison & Venville (1993) for instance, investigated the use of a wheel analog for the refraction of light and tentatively concluded that analogies may contribute to conceptual change.

Analogies have been referred to as "double edged swords" (Glynn, 1989, p.20) because although they can be beneficial in the ways outlined above, they can also be detrimental. Analogies have been shown to be responsible for students having alternative conceptions, ideas different from accepted scientific beliefs. This is believed to be caused by students transferring unique features of the analogical concept to the scientific concept which should not be transferred. Gentner & Gentner (1983) for example, found that people who think of electricity as though it were water import ideas from the domain of flowing fluids when they reason about electricity. Other problems centre around students being unfamiliar with the analog, or having a different conception of the analog compared with the teacher. Analogies also become superfluous if the students already have a good understanding of the science concept. The use of analogies in this situation simply adds to the "classroom noise" (Johnson & Al-Naeme, 1991). The problem, therefore, becomes a question. How can science teachers utilise analogies for their visualisation, motivational and constructivist qualities while avoiding confusion, and the development of students' alternative conceptions?

Approaches for the use of analogies in science teaching have been developed (Clement, 1987; Dupin & Johsua, 1989; Gentner, 1983; Glynn, 1989; Zeitoun, 1984). Although each of these approaches has meritorious aspects and have been built from credible theory, they seem to have limitations with regard to their suitability to the science classroom. It is interesting to note that none of the above approaches to the use of analogies in science teaching were developed in collaboration with the teachers for whom they were intended. It is not surprising, therefore, that there has been little effort to train teachers in the effective use of analogies.

The most useful of these models in terms of the classroom situation is Glynn's (1989) Teaching-With-Analogies (TWA) Model. This model was developed from the examination of exemplary textbook analogies and key operations performed by the authors were incorporated into a six step model which was designed as a guide for teachers and authors of science textbooks. None of the six operations of the TWA Model involves consideration of the students' prior conceptions, a fundamental element in a constructivist approach to teaching science (Duit, 1991). Additionally, this model neglects to direct the teacher to assess the appropriateness of the analog for her or his particular students. The limitations of this model seem to be a result of it being developed from textbook analogies. The interaction that occurs between teacher and students and the dynamic nature of the classroom are overlooked.

During the past three years, the analogy research group at the Curtin University of Technology have been working with science teachers to observe their use of analogies in science lessons and to develop, implement and evaluate systematic teaching approaches whereby analogies can be used more effectively. Part of this work has been reported in detail in this paper where one teacher used an analogy for explaining refraction. During this collaborative work with science teachers we have been using Glynn's Teaching-With-Analogies Model as the basis of teacher inservice into the use of analogies in the classroom. As might be anticipated the competent teachers with whom we are working interpreted the Glynn model in their own way and further modified the teaching approach for incorporating analogies into their science teaching. The resultant teachers' use of Glynn's model and our own analyses of that teaching has enabled us to develop a simpler and what at this stage appears to be a more effective and efficient three-phase model of analogy teaching.

In teaching with analogies, teachers initially considered the concept to be taught (was it difficult, unfamiliar or abstract?), whether or not the students already know something about the target concept, and whether or not the students were familiar with the analog. This Focus on analogical instruction took place both before and within the early part of the lesson, depending upon the circumstances. During the class presentation of the analogy, teachers paid careful attention to the likes and unlikes between the analog and target, discussing features of both the analog and target and drawing similarities between them as well as ways the analog and target are not alike. We have called this the Action phase of analogical teaching. Following the presentation of the analogy, teachers reflect on the clarity and usefulness of the analog and consider ways in which the analog and consider ways in which the analog may be improved. this Reflection phase may take place within the lesson itself or after the lesson as later preparation occurs. We have observed that in practice these phases are not distinct but run into one another.

To assist teachers in analogical instruction based on our research, we have produced a guide for teaching and learning science with analogies. In doing so, we use the three phases of the teaching approach, Focus, Action and Reflection, to form the acronym FAR (see Figure 1). The purpose of the FAR Guide is to help teachers maximise the benefits and minimise the constraints of analogies when they arise in classroom discourse or in textbooks. The guide has come about as a result of may hours observing and interviewing teachers and students and has been designed, as much as possible, to reflect the skilled way in which an exemplary, practised teacher uses analogies in their teaching of science. Our hope is that the steps of the FAR Guide become second nature to those who have been familiarised with it and that they are usefully applied to the teaching of analogies. Most of all, we hope that teachers and their students benefit from, and enjoy analogies when teaching and learning science. As we work with teachers to assist them in improving their teaching, we will continue to allow our teaching approaches to be influenced by our research and for them to develop. We are now engaged in further research whereby we can better understand how students learn by analogies.

Analogies in Electricity: a Help or a Hindrance?

Introduction

For the past decade, there has been considerable research into alternative conceptions held by students and teachers about electric current in simple circuits (Osborne 1981, Shipstone 1988). As a result of this research, diverse remedial strategies have been investigated, in particular the use of analogies (see, for example, Dupin and Johsua 1989, Arnold and Millar 1988). These strategies have had only moderate success, however, because students' alternative conceptions have been found to be very persistent (Duit, Jung and von Rhoneck 1985). In order to understand the origins of these conceptions, it is helpful to examine the kind of images which young students bring with them into the classroom before receiving any formal tuition in electricity. How do these images differ from the more sophisticated ones held by experts, and what kind of images do we want students to have in order to be able to use electricity with confidence and to solve problems at a higher level? In this paper, the kinds of images held by various groups are reviewed with particular reference to common analogies presented in the classroom. Some useful images are identified.

Young images

Background

The topic of electricity is one in which young students bring to their first lessons some perceptions and conceptions which have their origin in life-world experiences, largely in the home. Solomon, Black, Oldham and Stuart (1985) investigated the images of young students in Britain who, as the authors point out, had "lived amongst electrical appliances for as long as they can remember" so that they had formed a "store of life-world knowledge, with any associated folklore and emotional overtones". In assessing this knowledge, the authors avoided formal testing and asked for free writing, similes and picture analysis from the students.

Students were given five similes from which to choose. These were that electricity is like: fire, a river, a dangerous animal, fuel, or lots of tiny particles. Multiple responses were accepted. Many students in this group selected the "dangerous animal" or the "fuel" simile, but all similes were popular except "a lot of tiny particles". In this respect, Solomon et al. (1985) reported one observation of particular interest. Some students had rejected the particle simile:

...on the grounds that something which flowed had to be continuous ...and not particles. This thoughtful answer came from pupils in different schools and seemed curiously reminiscent of the ancient Greek arguments about atoms and the continuum. Scientists use of the word 'flow' in the context of particles may be more at odds with its normal use, in the context of fluids, than we realize. (p.289)

A small group of 14 year-old girls (N = 25) in Western Australia was tested prior to teaching their first electrical unit to see whether their images mirrored those discovered by

Solomon et al. (1985) for English children. The results for this group are compared with their English counterparts in Table 1.

Table 1

Summary of responses from the research of Solomon et al. (1985) compared to a group of similar students in Western Australia

Percentage who chose the simile

	English students		Australian students
	Younger group	Older group	
Like			
a fire	52	66	60
a river	51	71	40
a dangerous animal	85	88	52
a fuel	72	76	60
a lot of tiny particles	35	38	28

Some of the Western Australian students who chose the simile "like a lot of tiny particles" explained their choice in terms which indicated some confusion:

"Electricity has lots of tiny particals (sic) in it"

"Electricity is like lots of tiny particles working together to make light, lightning, sound and many more things. If one of these particals (sic) did not work, the outcome would be different"

"Electricity is made up of many volts"

Only two students in this group mentioned negative and positive particles.

Of those who chose the "river" image, all but one explained their choice in terms which included the words "flow" or "run"; the remaining student mentioned the presence of currents to justify the river simile. The "dangerous animal" image, while less popular with the WA group, was still selected by over half of the students as being appropriate. Results of this research seem to point unequivocably to what Solomon et al (1985) refer to as a common culture of knowing, saying and emotive reactions which is available to all these children. Overall, the similarities with the results obtained by Solomon et al. (1985) are striking, and indicate that the stock of life-world knowledge available to students in Australia is probably very similar to that in England.

In follow-up interviews, it became clear that the Australian students actually had little understanding of common electrical terms and were confused about their scientific meaning:

"Volts are -like- carried through the electricity and in the power lines there's a certain amount of volts I'm not really sure..."

"Current - is that when it's just carried along?"

"Volts are the amount of electricity - it's hard to explain"

"Current is like lots of electricity - bits - all going through in a wiggly line"

Many beginning students do not have alternative conceptions about the mechanics of conventional circuitry because they have not encountered it in their life-world experience, but they have already gathered information and images about electricity which may cause problems for the teacher. Their electrical vocabulary, for example, is generally limited and may be loose and inaccurate. Words such as "power" and "energy", "current" and "voltage" may have been encountered in a muddled and non-specific way.

High school and post-secondary images

Background

Once students begin formal tuition in the topic of electrical circuitry, they are required to have a more formally constructed understanding of the nature of electricity. The models which students may adopt at this stage have been described by Shipstone (1984) in the following terms:

Model 1: Current leaves the battery at both terminals and is used up within the circuit elements. Osborne (1981) refers to this as the 'clashing currents ' model.

Model 2: Current flows in one direction around the circuit, becoming gradually weakened as it goes so that later components receive less. Lamps furthest along the circuit will be least bright.

Model 3: Current is shared between the components in a circuit. If lamps are identical, current will be shared equally but not conserved.

Model 4: The current is the same throughout the series circuit (the 'scientific' view).

(Shipstone found that these models were hierarchical and that by age 17 only about 60 % of students had progressed to Model 4.)

Shipstone's hierarchical model has been found to be ubiquitous amongst students in many countries. In 1980, for example, Fredette and Lochhead (1980) had detected the concept of an "electric sink" (broadly, Model 2) in freshman engineering students in the United States; Cohen, Eylon, and Ganiel (1983) in Israel tested 145 high-ability upper high school students and 21 senior physics teachers with physics degrees: Most of the students were perceived to be "current-orientated" - they believed that the current leaves a battery at a particular value and is modified thereafter depending on what it encounters in its path. This is Model 2. Many of the teachers did not hold a theory of current conservation (Model 4) either. In Western Australia, 175 university physics students were administered an instrument to assess qualitative understanding of basic concepts of electricity (Treagust & Zadnik, 1991) and preliminary results from this study indicate the same trends.

In broad terms, the 'scientific view' presented to such students by teachers and lecturers is one of direct current being due to the flow of charged particles, usually electrons, under the influence of a potential difference across the ends of a wire. This model generally requires students to have a rudimentary knowledge of atomic structure. The mental images associated with this model are reinforced by common analogies used by many teachers and in many textbooks.

The Water Model

The analogy between the flow of current and the flow of water has been popular for the more than a century. It draws parallels between water pressure and voltage, flow of water and current, and constricted pipes and resistance. Early texts introduced the term "electrical pressure" as an analogy for voltage and this is still widely used, particularly in engineering texts. Texts by Maycock (1919) and Jamieson (1919), intended for use by students of electrical engineering, both feature the water analogy; the same analogy has appeared also in many books intended for use by secondary students of physics. Many recent physics and engineering texts quote the analogy in a form very little different from the texts of the 1900s. In the water model, the pump is analogous to the battery: early examples of this model are shown in Figures 1a and 1b but its form and general features are still found in current texts. A concrete model of the water circuit was recommended laboratory equipment for the Nuffield Science programme (Nuffield, 1966).

Figure 1a: Hydrostatic analogy of fall of potential in an electric circuit due to Millikan and Gale (1913)

Figure 1b: Hydrostatic analogy due to Maycock (1919)

Gravitational Analogies

Deschanel (1885) favoured a gravitational analogy for potential difference, likening a loss of potential energy on descending a hill to the energy lost "when positive electricity is allowed to run down from a conductor of higher to one of lower potential". This analogy has been revived and extended in some recent texts, with variations. The treatment by Giancoli (1991), for example, almost exactly echoes Deschanel's discussion of potential energy variations, while that of Halliday and Resnick (1988) introduces the idea of resistance in a gravitational circuit. In Halliday and Resnick's (1988) text, a girl picks up balls and pushes them into a horizontal pipe. Emerging from this pipe, the balls fall down a vertical tube filled with a viscous fluid. In this circuit, the girl is analogous to the battery, giving the balls potential energy; the pipe is analogous to leads in a circuit; and the vertical tube is the "resistance". It is clear that this last analogy will create a 'billiard-ball' image of electric current in the mind of the reader.

Anthropomorphic Analogies

A third analogy which has become popular in more recent texts is based on anthropomorphic ideas. The notion of electrons rushing along a wire carrying energy from one point to another has lent itself to some colourful descriptions of electric circuits, the most noteworthy being George Gamow's "gay tribe of electrons" (Gamow, 1971). Mr Tompkins, Gamow's adventurous explorer of other worlds, finds himself in the role of a conducting electron in a copper wire:

Rather tired after his breakneck flight through space, Mr Tompkins tried at first to get a little rest on a steady orbit of one of the copper atoms. However he was soon infected with the prevailing vagabondish feeling of the crowd, and he joined the rest of the electrons in their nowhere-in-particular motion. (p. 115)

The idea of electrons with personalities is a recurring theme. It is difficult to predict with confidence what mental images result from using this last analogy, but there seems little doubt that the use of the water model and the gravitational analogy, especially as presented in Halliday and Resnick (1988), will lead to specific mechanical images. In a study designed to elicit these images from students, three groups in their first year of post-secondary education in Western Australia were asked about the images that they held of electrical terms: these are discussed in the next section.

Images After Preliminary Post-secondary Instruction

Electrical topics form the subject of lectures to post-secondary students at technical colleges in the electrical trades, and at university in physics and applied physics courses. A number of such lectures were observed and three groups were selected for the administration of a questionnaire about the kinds of electrical imagery and metaphors which the language of the lecturer had evoked.

The Technical College Students

Two groups of first-year apprentices were observed for the duration of their introductory electrical course (about 11 weeks). The first group of students were apprentice electricians; the second group were 'other trades' - mainly welders, boilermakers and sheet metal workers. Each group attended the college on only one day a week, and spent the remaining days on the job practising their trade. At the end of the course, a number of electrical metaphors used by the lecturer were presented to the students to try to evoke some images of simple electrical terms. The responses of the students were requested either in sketch or verbal form, whichever came most immediately to mind.

The five metaphors used by the lecturer were:

1. "Force from the battery dislodges an electron and it moves through the copper conductor"
2. "Power is consumed from the supply and converted into mechanical power to turn the shaft of the appliance"
3. "The resistance tries to restrict the flow of current"
4. "There will be an electromotive force driving the current"
5. "Throughout the circuit we get our voltage dropping"

The responses from the two groups are summarised in Table 2, Parts 1 and 2.

Table 2
Images and verbal responses of apprentice tradesmen to electrical metaphors
Note: Italicised text indicates analogical imagery

Part 1
Group1: electrical apprentices (N=12)

Metaphor 1: "Force from the battery dislodges an electron and it moves through the copper conductor"

Drawing responses	Verbal responses	No response
Traditional stylised circuit diagram (4)	'What starts and makes electrons flow'(2)	1
Battery cross sectn, wire coming out, arrows	'Copper conductor gains electrons'	
Wire cross section, arrows	'Voltage'	
	'A ball going very fast running into another ball'	
	'Little men transferring electrons round and round'	

Metaphor 2: "Power is consumed from the supply and converted into mechanical power to turn the shaft of the appliance"

Drawing responses	Verbal responses	No

response
Fan plugged into wall Traditional motor explanation (4)
2
socket or circuitt (2 'Which you can use to drill a hole'
Man cranking shaft handle 'Drills, mixers, saws'
Picture of food to man to
'energy'

Metaphor 3: "The resistance tries to restrict the flow of current"
Drawing responses Verbal responses No
response
Small man pushing balls electron flow explanation (3)
1
back against flow 'Current inversely prop. to resistance'
Fireman with hose ‘Like a hose with a knot'
Constricted hose

Knot in hose
Speed bumps on a road
River image with arrows

Metaphor 4: "There will be an electromotive force driving the current"
Drawing responses Verbal responses No
response
stylised circuit (3) 'Voltage moving electrons'
5
power point 'Force that is needed to move electrons'
V with arms, pushing big I
Car, emf driving, current
passenger

Metaphor 5: "Throughout the circuit we get our voltage dropping"
Drawing responsea Verbal responses No
response
conventional circuit (2) Voltage across components (4)
2
Linear graph 'The loads use the voltage'
Fat tube full of Vs, going to 'Little volts filling inside
an appliance
thin tube and staying there'

Table 2 continued
Images and verbal responses of apprentice tradesmen to electrical metaphors
Note: Italicised text indicates analogical imagery
Part 2
Group 2: Other trades (N=13)

Metaphor 1: "Force from the battery dislodges an electron and it moves through the copper conductor"
Drawing responses Verbal responses No response
Traditional stylised 'How electricity travels'
6
circuit diagram (2) 'Circuit'
Electron ball half way between
battery and copper slab
Atom model with dislodged
electron
Electron -person moving into pipe,
another emerging with parachute

Metaphor 2: "Power is consumed from the supply and converted into mechanical power to turn the shaft of the appliance"
Drawing responses Verbal responses No response
Stylised circuit 'The magnetic force which attracts'
6
Fan plugged into wall 'Starter motor' (2)
"power" person riding bike 'To turn spindle on lathe'
Cogs and wheels with battery
with huge lips and teeth

Metaphor 3: "The resistance tries to restrict the flow of current"
Drawing responses Verbal responses No response
Stylised cross section of wire 'Heater'
7
Electron balls approaching a
barrier
Flow arrows approaching a
barrier

River image with arrows
Stop sign and arrows

Metaphor 4 :"There will be an electromotive force driving the current"
Drawing responses Verbal responses No response
Traditional stylised circuit 'Use an ammeter to find emf' (2)
4
Emf lines towards a current 'ball' 'Battery, power source'
Croquet mallet type emf hitting 'Volts'
current ball
Car driving current

Truck, "current" on back

Metaphor 5: "Throughout the circuit we get our voltage dropping"

Drawing responses	Verbal responses	No response
Stylised circuit	'Use a voltmeter to find voltage drop '(2)	4
Linear graph	'Series circuit'	
Plane dropping Vs	'Resistors'	
Cliff, "voltage" falling off (2)		

From Table 2 it may be seen that the electrical apprentices had recourse to a richer pool of analogous images than the corresponding apprentices in other trades. Since both were receiving the same instruction, it may be concluded that the electrical group were using some of the language and metaphor of the practising electricians with whom they spent most of the week. There is, nevertheless, strong evidence that both groups did not have clear images and were still confused about many electrical terms. Most of the analogies were not especially useful in terms of enhancing understanding of the terms represented, and, in some cases, were definitely misleading. The anthropomorphic nature of the language used by the lecturer was entirely consistent with the images invoked, such as "power consumed" eliciting the image of huge teeth - but the fact that large numbers of both groups left blank spaces, especially in the sections on resistance and electromotive force, indicates confusion and lack of confidence. Verbal responses were generally not especially helpful, often consisting of single words which conveyed little or no meaning.

The University Students

A similar questionnaire was given to a group of radiography students in their first university year, who had completed a regular applied physics unit on introductory electricity. All of these students had studied high school physics.

The overwhelming conclusion from this exercise was that students in this group expressed few meaningful analogous images. Their responses were generally pictorial, with the largest number in each case choosing conventional circuit symbols or pictures to convey their thoughts. This may indicate superior understanding with no need for imagery, but the group also was tested for understanding of simple circuitry (Stocklmayer, Zadnik and Treagust 1993) and most appeared to be operating in a Shipstone (1984) Model 2 or Model 3 mode. Some responses were flippant or sarcastic, once again indicating that the students were unwilling or unable to express their understanding in a meaningful way.

The muddled responses given by these students are consistent with the research findings about students' understanding of simple circuitry which have been described earlier. This finding gives rise to the question of what we would like students to know about the nature of electric current and voltage. What images would we like them to have?

The teachers' images

A group of 31 high school and university teachers in Western Australia were asked about their own images of electricity and those they believed 14-year olds should have. Their responses were remarkably uniform. Almost all in this group (28) had a mechanical model of electricity which gave rise to images of electrons as small balls moving along tunnel-like wires. Twenty two of the group made no mention of the influence behind the movement: only six explicitly mentioned an electric field as the reason for the electric current. In this group, most did not present their answer as if it had personal relevance for them, but answered in a 'scientific' manner which cast little light on the real picture behind the words. Some examples of their answers to the statement: "My own mental model of electricity is..." include:

"An electric current is a flow of electrons from the negative terminal around the circuit and finally back to the positive terminal"

"rate at which charged particles (electrons, ions) pass a point in a conductor"

"electrons moving in a particular direction because of a driving force"

"particles which are carriers of energy and travel in a stream"

"a flow of charged particles in a direction"

"An electric field acts on the charged particles. The particles that are free to move are caused to drift as a result of this force..."

"Moving electrons or ions, moving under the influence of an electric field, colliding with atoms/other ions in their path.

"charged particles moving along a wire, activated and pushed by a voltage supplied by a battery or AC power source"

The mental image of the nature of the particles or electrons mentioned in these descriptions was not elaborated. Further questioning of some of the respondents, however, revealed that most often the image was of little balls. Five of the respondents drew pictures to explain their image and, in each case, the particles are spherical. Four of these diagrams are shown in Figure 2.

Of the remaining three of the 31 respondents, one had a mechanistic particulate view but the particles were "fuzzy electron clouds moving down a wire". Two presented analogies: one saw electricity as "a wagon wheel turning on its axle, mounted horizontally and doing useful things" and the other in terms of "water flowing through a thin pipe". Of the whole group of 31, 12 mentioned the word "flow" in their answer.

Figure 2: Diagrams given by teachers of their mental models of

electricity

Not surprisingly, when this group of teachers evaluated what they would like 14-year old students to know about electricity, their answers closely mirrored their own images. Nineteen of the group responded to this question and their answers are classified in Table 3.

This group of teachers clearly identified the particulate nature of electricity and the characteristics of circuits as being a priority for 14-year old students. While generally unaware of many of the research findings in this area, all of the group was conscious of the problems attached to teaching the concept. They ascribed these problems to the abstract, unseen nature of electricity, to confusion between current and voltage and to difficulties with the idea of current conservation. Despite this intuitive knowledge of students’ problems, their own models still formed the basis for their choices when asked to prescribe for young students.

TABLE 3
Teachers' views of what 14-year olds should understand about direct current electricity

Electricity as a model of particles flowing

unspecified particles	electrons	+/-	atomic structure
current direction	current conservation		

6 5 3 3
1 2

Other features
presence of field/p.d./ energy carrier conductors / safety
production application
battery insulators
4 5 1 3
1 1

Note: the total number of responses was 19. Those who indicated a particular area of understanding are listed; all 19 gave multiple responses.

Teachers of physics are, in general, graduates of a "pure" rather than an "applied" physics course. They rarely work with electricity on a regular basis and do not conduct research in this area. Their teaching material is obtained from a series of texts which have been shown to be repetitive and narrow in their language (Stocklmayer and Treagust in press). It is pertinent, therefore, to examine the kinds of images held by those whose daily work involves electricity, and the images held by earlier researchers who have specialised in the area of electrical development. These might be termed the "experts" in this field. Historically, electrical researchers were, in their time, experts whose imagery influenced their successors and, ultimately, our classroom practice today.

Expert images of electrical scientists

Electricians and electrical engineers are the inheritors of a long tradition of tinkering with electricity which goes back to William Gilbert (1544 - 1603). In Gilbert's time, the popular image of electricity was that of a "material effluvium" emitted by substances when rubbed: This material substance attracted other substances in the vicinity. Fluid images actually had their origins in antiquity, when the ancient Greeks had observed and described the properties of amber in fluid terms. It was the presence of fossil remains in amber which had led to the belief that it was a solidified fluid and that it had, in some mysterious way, qualities of life.

Electricity as Two Fluids

Images of electricity changed somewhat with Charles Dufay (1698 - 1739), a French experimenter who first described electricity in terms of two fluids. "Electricity is a quality universally expanded in all the matter that we know, and which influences the mechanism of the universe far more than we think" (quoted in Priestley 1959, p. 183).
As quoted in Magie (1969), Dufay said that:

nd on the contrary attracts all those of the resinous electricity.... (pp. 399-400)

The One Fluid Theory

Benjamin Franklin's famous kite experiment was actually the culmination of a series of investigations, which led Franklin to formulate a "one-fluid" theory. He initially regarded neutral bodies as being in equilibrium, a state which led to the notion of positive and negative amounts of a single electrical fluid. According to Franklin, electricity was a fluid which was common to all things, such that any body containing more than the normal amount was in the "vitreous" electrical state, while deficiency in the fluid resulted in the "resinous" state. Franklin called these states "positive" and "negative". He eventually formulated the idea that the fluid was within the body rather than around it, thereby implicitly disagreeing with a number of earlier researchers including Dufay. Essentially, the fluid was already present in both rubbed and rubbing materials, and the process caused its redistribution. It is from this imagery that the "direction of flow" was deduced to be from positive to negative, since positively electrified bodies were assumed to give up fluid to negatively charged bodies.

The work of Coulomb, who followed Franklin, provided a critical watershed in the development of electricity as a science, placing it for the first time on a mathematical foundation. Coulomb favoured the two-fluid theory, and reasoned entirely from this perspective. He also believed that there was a "magnetic fluid" which accounted for the phenomena of magnetism.

Thus, by about 1800, electricity was firmly established as a fluid phenomenon, consisting of either one or two fluids depending on whether one supported the Franklin School or the Coulomb School. There was still a strong sense that the fluid itself was independent of the matter associated with it, and that actual transfer of fluid occurred whenever electrification was observed. Increasingly, the language of electrical science reinforced the fluid idea. The next important contribution to electrical imagery was made by Michael Faraday.

Field Theory: a New Electrical Image

Michael Faraday (1791-1867) used his knowledge of discrepant events, and a unique ability to theorise without firm preconceptions, to reject the idea of electricity as a fluid. Faraday's view around 1831 may be summarised as an image of an electric wave being transmitted down a current-carrying wire and causing the particles within the wire somehow to align themselves.

Faraday realised that the effectiveness of both a magnet and a voltaic cell lay in their ability to transmit their effects along lines of force, not in the basic constituent parts of the magnet or cell. "The energy of the magnet, then, lay quite literally in the medium through which the lines of force passed, and not in the magnet itself. This was the fundamental concept of classical field theory" (Williams 1965, p. 452).

Faraday's images were entirely different from those of his predecessors in electrical research. At times, his expression of the nature of the image was less than clear, but his concept of a field and accompanying force lines proved a fruitful source of inspiration for James Clerk Maxwell to place this theory into a mathematical framework. Faraday's ideas of particulate action were closer to wave-like action than to Newtonian mechanics: it

is perhaps the view of hindsight to suggest that he was not operating in a Newtonian mode but certainly much of his imagery was of non-Newtonian behaviour. Maxwell, however, was more constrained by convention.

Mathematical Images

Maxwell's first paper ('On Faraday's Lines of Force' (1855 and 1856)), describes a mathematical relationship for Faraday's force lines. Maxwell often reasoned through analogies (Tolstoy 1981) and, in this case, he used a water model in which the lines of force corresponded to streamlines in the water and the electric charge was equivalent to a pump. Maxwell's use of this analogy was simply to illustrate in a concrete way the correspondence between electrostatics and hydrodynamics. He did not use the model for predictive analysis: Maxwell himself said "it does not, even in appearance, account for anything" (Papers, vol 1, quoted in Goldman 1983, p. 141). He was able to discard this model as soon as it became less useful, but he may have started a trend towards hydrostatic analogies for electric circuits.

Maxwell's imagery was always complex. There seems little doubt that the models were simply aids to his mathematical reasoning, but they confused his contemporaries who believed in a Newtonian aether and who could not conceive a mathematical scientific description which was not based soundly upon mechanics. For example, William Thomson (Lord Kelvin) could "never satisfy myself until I can make a mechanical model of a thing... As long as I cannot make a mechanical model all the way through I cannot understand, and that is why I cannot get the electromagnetic theory of light" (Lectures (1884), quoted in Goldman 1983, p. 196).

The field ideas of Faraday and Maxwell were therefore never brought into the mainstream of textbooks designed for secondary level students (Stocklmayer and Treagust in press) and the language of electrical science remained firmly grounded in fluid imagery.

Expert images of electrical practitioners

Practitioners in electrical fields have different images of electricity from those of physics students and teachers. In interviews with electricians, electrical engineers and physics lecturers who had worked extensively with electricity, a uniform view of what is useful emerged. All of those interviewed were concerned first with "the job" to be done by the electricity: What was its work in the circuit, and how best should the circuit answer this requirement? This more practical view of the purpose behind the circuit led inevitably to an mental image that was more global and holistic than the mechanistic electron view. Essentially, these practitioners were concerned with the circuit as a whole. This was expressed by various practitioners in different ways, depending on the clarity of their own image: for the electrician "what goes out must come back in"; for the engineer a more mathematical appreciation of circuit characteristics which, nevertheless, had a similar loop-like image. These images are fundamentally field-like, rather than atom-like, in their nature. Extracts from two interviews with reflective tertiary lecturers in physics and electrical engineering reveal the strength of their field concept.

The first interview was with a physics lecturer ("Lecturer A") who had considerable experience with electrical devices through his research interests:

A. I approach it from this energy perspective - how much of a kick is it going to give me?...Having been bitten, the mental image is of something that's going to give me a kick, so it's an energy-related feel, but what actually goes on inside the circuits is different from what effect it's going to have on you, in the sense that it's going to perform a useful function... But the energy concept is still there - of work being done by either the chemical effect or of getting work out of some exterior circuit or something... I don't tend to think of the flow of electrons very much - it's A. Well, I think it's just ground into us so much. I had that as well, I had that view as well - I can't tell you where it changed, I think it just changed in working with these devices - and you stare at the circuit and if you sit there and try and think about solving the problem in terms of little round balls, it's not going to work, but if you think of it in terms of the properties of the circuit, the material you have, the way that it's working, the fields that are there, the voltages that are there, then you can solve the problem - but real solutions don't come by thinking about little round balls.

I. So why is it that every physics teacher that I have asked this question tells me that their mental image is of little round balls moving along ... and I think mine was too, before I started this...

A..the classic question of when you turn the light switch on, why does the light come on instantaneously - I always ask that every year, about the second lecture that I give to the first year students, and without fail, they nearly always come up with: If you turn the light switch on, it pushes an electron up into the circuit and pushes an electron through. This idea would be about an eighty per cent response - and questions that I ask them - I don't do it deliberately - are definitely couched or set up in this billiard ball framework that they're trying to use to solve problems. So it makes it difficult in terms of when you get on to more complex, non-linear phenomena in AC and diodes and transistors - if the student still has that then, or if they still have it to a certain extent, it makes it very hard for them to know what's going on.

Echoes of the same feel for circuitry were expressed by the Lecturer B, a person of many years' experience in electrical engineering:

I. When you talk about electric current, in your mind are you envisaging a push, or a pull, or both?

B. Neither - you see, electric current is associated with an electric and magnetic field which gets propagated with a certain velocity, and these are terminal conditions indicating... in my mind, currents are associated with movement of charges - why are the charges moving? Well, if you go back and look at the physics, if you have an electric field in space then any charge placed in that field experiences a force. If it is free to move, then it will move in some fashion, so if you ask what is causing the charges to move - which constitutes the current - you see, your question is actually foreign to me. Is it a push or a pull? - I never think of it in terms of a push or pull at all. I simply say, suppose there are conditions which give rise to an electric field - now, you've got to say: what do we mean by an electric field? It depends how far you want to go back - if you start up a situation which is going to create a magnetic field, well then the whole field is propagated with a certain velocity. The best way is to think of a pair of wires - like a question I sometimes ask my students in second year. I say: 'I take a long length of light flex with a three pin plug at one end and a light bulb socket on the other. I put the light bulb in, turn it on and the light bulb lights up. Now this time, I'll do the experiment again - I take the light bulb out, plug it in, turn it on - how does the electricity know not to flow into the cable, that there's no light bulb in, until it flows in - to discover that there's no light bulb in?' O.K.? Simple question?

I. Yes?

B. What's going on? Now what actually happens is that electric and magnetic fields get established across the wires and get propagated at the velocity of light and as they flow down,

energy's flowing because voltage is across the cable, and there's current flowing into it due to magnetic fields, so its all flowing in, down to - at the end, you get a reflection because you can't get any current going out through the discontinuity, the open circuit at the end. So you get a current wave, or a magnetic field wave, being reflected back, cancelling out all the magnetic field on this side and keeping a magnetic field on the other side until it gets back to the input, and at that point no more current flows in and there's voltage across the whole wire and you reach equilibrium. If you ask what's happened to the energy that's gone in in the meantime, while all that's taking place - you can work out mathematically that it's all stored in the electric field of the capacitance between the two wires - it all neatly balances out. So if you ask me what do I think about electric current and what's pushing it and pulling it, I think of it as being associated with the electric and magnetic fields, of which the currents are, if you like, a boundary condition.

I...and the more I think about that kind of image, the more I realise how very dramatic and powerful it is and I wonder why we avoid it with students..

B.,..Well, which image is right? The answer is - none of them are right - they are all concepts which have proved useful to us, and in so far as they have proved useful, the more generally they have proved useful the more 'real' we call them - but none of them are real.

All the electrical engineers interviewed believe that the mechanistic picture of electric current is not, in the long term, useful to students. The field concept, whether expressed as such directly or explained more indirectly, was the most useful way in which they thought of electrical phenomena. Only teachers of physics expressed the electron flow model as the most useful for their students, and used various particulate analogies to enhance understanding.

Conclusion

Children coming into high school have a vague and often fearful image of electricity. Once they encounter formal circuitry they are required to understand a mechanistic model of electron movement through a wire which, by analogy and metaphor, is closely allied to fluid transfer. All the language of electricity reinforces this model. The belief that electricity is a fluid has been discarded for many years by professional physicists and engineers, yet we retain the terms in our electrical vocabulary which will create fluid images in the minds of students.

Experts, whether they be modern practitioners of electrical science or earlier researchers, in particular Michael Faraday, do not retain this model. They regard electricity as a field-like phenomenon, formed of endless loops, and their understanding is inextricably tied to the concept of electricity as useful energy. Their vocabulary deals with the task, the load, the job and the field - and they find the micro-view of electron transfer irrelevant and, at times, confusing.

Teachers of electricity have a strong belief that the particulate model is both useful and "correct". They themselves hold this image, and few have a strong field concept. Clearly, however, their students have difficulty with the model and hold misconceptions and alternative conceptions about circuit behaviour which lead to difficulties with problem-solving. The electron-transfer model is ubiquitous: it appears in all texts whether they be designed for physics or engineering students or for electricians.

Changing the perceptions of what constitutes useful knowledge in electricity is a difficult and challenging task. It is important, however, to address the problems experienced by students in this subject, because a working understanding of electricity is a fundamental aspect of scientific literacy.

Research indicates that students do not have this understanding and that they have problems with conventional circuitry. Those who work with electricity do not need the old model of current as electron flow: perhaps we should examine its usefulness for the next generation of students whether they are proceeding to a career in electricity or not.

References

Arnold, M. & Millar, R. (1988). Teaching about electric circuits: a constructivist approach. The School Science Review, 70 (251),149-151.
Bean, T. W., Searles, D., Singer, H., & Cowan, S. (1990). Learning concepts from biology text through pictorial nalogies and an analogical study guide. Journal of Educational Research, 83.,233-237.
Brown, D. E., & Clement, J. (1989). Overcoming misconceptions via analogical reasoning: Abstract transfer versus explanatory model construction. Instructional Science, 18, 237-261.
Cohen, R., Eylon, B., & Ganiel, G. (1983). Potential difference and current in simple electrical circuits: a study of students concepts. American Journal of Physics, 51 (5) 407-412.
Curtis, R. V. & Reigeluth, C. M. (1984). The use of analogies in written text. Instructional Science, 13, 99-117.
De Jong, O. & Acampo, J. (1992, June). Translating textbook content into classroom practice: chemistry teachers' actions and reflections. Paper presented at the 17th annual conference of the Association for Teacher Education in Europe, Lahti, Finland.
Deschanel, A. P. (1885). Elementary Treatise on Natural Philosophy. London, Blackie and Son.
Duit, R. (1991). On the role of analogies and metaphors in learning science. Science Education, 75, 649-672
Duit, R., Jung, W., & Von Rhöneck, C. (eds). (1985). Aspects of Understanding Electricity. Kiel, Germany, Institute for Science

Education.
Dupin, J. J., & Johsua, S. (1989). Analogies and "modelling analogies" in teaching. Some examples in basic electricity. Science Education, 73, 207-224.
Dupin, J., & Johsua, S. (1989). Analogies and "modeling analogies" in teaching: Some examples in basic electricity. Science Education, 73, (2), 207-224.
Fredette, N., & Lochhead, J. (1980). Student conceptions of simple circuits. The Physics Teacher, 18 (3), 194-198.
Gabel, D. L. & Sherwood, R. D. (1980). Effect of using analogies on chemistry achievement according to Piagetian level. Science Education, 64, 709-716.
Gabel, D. L. & Sherwood, R. D. (1984). Analyzing difficulties with mole-concept tasks by using familiar analog tasks. Journal of Research in Science Teaching, 21, 843-851.
Gamow, G. (1971). The gay tribe of electrons. In Mr Tompkins in Paperback (pp. 112-127). London, Cambridge University Press.
Gentner, D., & Gentner, D. R. (1983). Flowing waters or teeming crowd: Mental models of electricity. In D. Gentner & A. L. Stevens (Eds) Mental models. pp. 99-129. Hillsdale, N. J.: Erlbaum.
Giancoli, D. C. (1991). Physics: Principles with Applications. London, Prentice-Hall International Inc.
Glynn, S. M. (1989). The teaching with analogies (T.W.A.) model: Explaining concepts in expository text. In K. D. Muth (Ed.), Children's comprehension of narrative and expository text: Research into practice (pp. 99-129). Newark, DE: International Reading Association.
Glynn, S. M. (1991). Explaining science concepts: A Teaching-With-Analogies model. In S. M. Glynn, R. H. Yeany and B. K. Britton (Eds.), The Psychology of Learning Science (pp. 219-239). Hillsdale, NJ, Erlbaum.
Glynn, S. M., Britton, B. K., Semrud-Clikeman, M. & Muth, K. D. (1989). Analogical reasoning and problem solving in textbooks. In J. A. Glover, R. R. Ronning and C. R. Reynolds (Eds.), Handbook of Creativity: Assessment, Theory and Research (pp. 383-398). New York, Plenum.
Goldman, M. (1983). The Demon in the Aether. Edinburgh, Paul Harris.
Guba, E. G., & Lincoln, Y. S. (1989). Fourth generation evaluation. Newbury Park CA: Sage Publications.
Halliday, D., & Resnick, R. (1988). Fundamentals of Physics. New York, John Wiley and Sons.
Harrison, A. G. (1992). Evaluation of a model for teaching analogies in secondary science. Unpublished Master's thesis, Curtin University, Perth, Western Australia.
Jamieson, A. (1919). A Practical Elementary Manual of Magnetism and Electricity. (E. S. Andrews, Trans.). (Tenth ed.). London,

Charles Griffin and Co. Ltd.
Johnstone, A. H., & Al-Naeme, F. F. (1991). Room for scientific thought. International Journal of Science Education, 13, 187-192
Joyce, B. R., & Showers, B. (1983). The integration of research and practice. In B. R. Joyce & B. Showers, Power in staff development through research in training Alexandria, VA: Association for Supervision and Curriculum Development.
Knox, K. & George, A. (1990). Close packing - a dynamic demonstration. Journal of Chemical Education, 67, 700-701.
Licata, K. P. (1988, May). Chemistry is like a ... The Science Teacher, 55(8), 41-43.
Magie, W. F. (1969). A Source Book in Physics. Cambridge, Harvard University Press.
Maycock, W. P. (1919). Electric Lighting and Power Distribution. London, Sir Isaac Pitman and Sons, Ltd.
Merriam, S. B. (1988). Case study research in education. San Francisco: Jossey-Bass.
Miller, G. A. (1979). Images and models, similes and metaphors. In A. Ortony (Ed.), Metaphor and thought. pp. 202-250. Cambridge: Cambridge University Press.
Millikan, R. A., & Gale, H. G. (1913). A First Course in Physics. Boston, Ginn and Co.
Nuffield Foundation (1966). Nuffield Physics Teachers' Guide I. London, Longmans/Penguin Books.
Olivera, M. T., & Cachupuz, A. F. (1992, March). Pupils' understanding of atomic structure and the interactive use of analogy. Paper presented at the Annual Meeting of the National Association for Research in Science Teaching, Boston, MA.
Osborne, R. J. (1981). Children's ideas about electric current. New Zealand Science Teacher, 29, 12-19.
Patton, M. Q. (1990). Qualitative evaluation and research methods. Newbury Park, CA: Sage Publications.
Priestley, H. (1959). Introductory Physics: An Historical Approach. London, John Murray Ltd.
Shapiro, B. L. (1988). What children bring to light: Towards understanding what the primary school science learner is trying to do. In P. Fensham (Ed.), Development and Dilemmas in science education. London: Falmer Press.
Shapiro, M. A. (1985). Analogies, visualisation and mental processing of science stories. Paper presented to the Information Systems Division of the International Communication Association, Honolulu, HI.
Shipstone, D. (1988). Pupils' understanding of simple electrical circuits. Physics Education, 23 , 92-96.
Shipstone, D. M. (1984). A study of children's understanding of electricity in simple DC circuits. European Journal of Science Education, 6 (2)185-198.
Shulman, L. S. (1986). Those who understand; knowledge growth in

teaching. Educational Researcher, 15(2), 4-14.
Solomon, J., Black, P., Oldham, V., & Stuart, H. (1985). The pupils' view of electricity. European Journal of Science Education, 7 (3), 281-294.
Stocklmayer, S. M. & Treagust, D. F. (1993, April). Understanding electricity through analogies; a historical perspective of conceptual change. Paper presented as part of a symposium on "Using analogies to engender conceptual change" at the American Educational Research Association, Atlanta, GA.
Stocklmayer, S. M., & Treagust, D. F. (In press). A historical analysis of electric currents in textbooks: a century of influence on physics education. Science and Education.
Stocklmayer, S. M., Zadnik, M. G., & Treagust, D. F. (1993). Working paper on university physics students' mental images of electricity. Perth, Curtin University of Technology.
Sutula, V., & Krajcik, J. S. (1988, September). The effective use of analogies for solving mole problems in high school chemistry. Paper presented at the Annual Meeting of the National Association of Research in Science Teaching, Lake Ozark, MO.
Thiele, R. B. & Treagust, D. F. (1991). Using analogies in secondary chemistry teaching. The Australian Science Teachers Journal, 37(2), 10-14.
Thiele, R. B. & Treagust, D. F. (1993, April). An interpretive examination of high school chemistry teachers' analogical explanations. Paper presented at the annual meeting of the American Educational Research Association, Atlanta, GA.
Tobin, K. (1990). Social constructivist perspectives on the reform of science education. Australian Science Teachers Journal, 36, (4), 29-35.
Tolstoy, I. (1981). James Clerk Maxwell: A Biography. Chicago, The University of Chicago Press.
Treagust, D. F. (in press). Understanding as representation: The importance and use of analogies in teaching and learning science. In L. Ingvarsson (Ed.), Professional Standards for the Teaching of Science. Science Education Professional Development Project, Monash University, Victoria, Australia.
Treagust, D. F., & Zadnik, M. G. (1991). A qualitative understanding of physics and chemistry concepts: is it worth the trouble? In M.W. Hackling (ed.), Proceedings of 16th Annual Conference of Science Education in Western Australia, (pp 145 - 154), Claremont, WA.
Treagust, D. F., Duit, R., Joslin, P. & Lindauer, I. (1992). Science teachers' use of analogies: Observations from classroom practice. International Journal of Science Education, 14, 413-422.
Treagust, D. F., Harrison, A., & Venville, G. (1993, April). Using an analogical teaching approach to engender conceptual change. Paper presented at the Annual meeting of the American Educational Research Association, Atlanta, GA.
Treagust, D. F., Thiele, R. B., & Venville, G. (1991) An analysis

of teaching approaches incorporating analogies. Working paper: Teachers' use of analogies project. Science and Mathematics Education Centre, Curtin University of Technology, Perth, Western Australia.
Wallace, J., & Louden, W. (in press). Qualities of collaboration and the growth of teachers' knowledge. Qualitative Studies in Education.
Webb, M. J. (1985). Analogies and their limitations. School Science and Mathematics, 85, 645-650.
Williams, L. P. (1965). Michael Faraday. London, Chapman and Hall.
Yin, R. K. (1988). Case study research: Design and methods. Beverly Hills, CA, Sage Publications.
Zeitoun, H. H. (1984). Teaching scientific analogies: a proposed model. Research in Science and Technological Education, 2, 107-125.

Chemistry Textbooks

Bucat, R. J. (Ed.). (1983). Elements of chemistry (Vol. 1). Canberra, Australian Academy of Science.
Bucat, R. J. (Ed.). (1984). 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.
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.
McTigue, P. T. (Ed.). (1979). Chemistry - key to the earth. Melbourne, Melbourne University Press.