Teaching About Conduction Using the Domino Analogy: A Case Study of One Teacher's Approach

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Abstract

This paper describes an investigation in which the researchers and an expert science teacher trialed a systematic approach for teaching analogies. Science contains many abstract concepts that rely upon analogy for their explanation and while the shared attributes enhance may learning, unshared attributes may compromise student understanding. This case study examines the process for integrating an innovation into a teacher's strategy repertoire and also examines the resultant lesson from the perspective of student understanding of conduction. The lesson discourse and teacher interview were tape recorded; for the next lesson the students completed an analogy mapping exercise and selected students were interviewed. Analysis of the resultant data suggests that student understanding approaches the desired outcome when familiar analogies are systematically presented in science.

Teaching With Analogies

Whenever a teacher is challenged to explain a difficult or highly abstract concept, analogies may be employed. This is particularly true when the abstract concept involves atoms and molecules or where the phenomenon cannot be easily described in purely scientific terms. Throughout history, scientists such as Kepler (Bronowski, 1973), Huygens (Duit, 1991), Maxwell (Gee,

1987) and Rutherford (Pimental, 1963) to name but four, have developed their theories and/or explained them using analogies. For instance, Oppenheimer (1955) and Starling and Woodall (1955) assert that light's wave nature can only be explained analogically and to this day (Hewitt, 1987, Serway, 1990) analogy remains the only satisfactory method for explaining the refraction of light.

Analogy is a culturally embedded means for explaining the difficult or inexplicable and its use ranges from children's stories through literature, religion, mathematics and science. While many teachers freely use analogies, there is a significant body of research indicating that analogies are "two-edged swords" as far as student cognition is concerned (Duit, 1991; Glynn, 1991). The central question when teaching with analogies is to ask, Do the students visualise the analogy in the way the teacher meant it to be understood? Can the students apply the analogy to the current phenomenon in a way that enhances their understanding of that scientific conception? and, Are the students able to recognise the analogy's limitations? These and other concerns stemming from the random use of analogies in the classroom led us to examine the science education literature resulting in the identification of three valid models for teaching with analogies (Clement, 1987; Glynn, 1991; Zeitoun, 1984).
Subsequent analysis of these three models led us to conclude that Glynn's Teaching-With-Analogies (TWA) model had the greatest potential to enhance teacher presentation of analogies while reducing the incidence of alternative student conceptions. Glynn developed his six step TWA model from an analysis of analogy use in science textbooks. The concept familiar to the students is termed the analog, the science concept being studied is called the target, and the links between the analog and target are called mappings which have both shared and unshared attributes. While each step in Glynn’s approach is important, the order in which the steps are used depends upon the teacher's style, the particular concept and the analogy being used. We modified Glynn's TWA model by reversing steps 5 and 6 and the modified TWA model for teaching with analogies follows:

1. Introduce the target concept to be learned - give a brief or full explanation depending on how the analogy is to be employed.
2. Cue the students' memory of the analogous situation - introduce the analog so that its familiarity to the students can be estimated by discussion and questioning.
3. Identify the relevant features of the analog - explain the analog and identify its relevant features at a depth appropriate to the students' familiarity with the analog.
4. Map out the similarities between the analog and the target - teacher and students identify the relevant features of the target

concept and clearly link these with the corresponding features of the analog.

5. Indicate where the analogy breaks down - note alternative conceptions that the students may be developing and known areas where the analog and target do not correspond. Point these out to the students to discourage incorrect conclusions about the target from the analogy.

6. Draw conclusions about the target concept - summarise the important aspects of the target concept.

Our current empirical data indicate that Steps 2, 4 and 5 are the points where student understanding often fails to match the teacher's expectations.

At Step 1, three approaches are possible. When the analogy is used as an advance organiser, the target concept is introduced after the analogy. When the analogy is used to develop the concept, the concept should be taught in sufficient detail to make the analogy relevant. When the analogy is to be used as revision, the concept is fully taught. Overall, teachers can enhance analogical instruction by choosing an appropriate analogy before the lesson and by carefully planning how it will be taught.

It is generally recognised that analogies generate meaning through a constructivist pathway (Duit, 1991). Students come to science instruction with tenaciously held preconceptions about their world; however, these intuitive ideas are often ignored by teachers. Similarly, students have their life-view of each analog used by their teacher and when the meaning a student attributes to an analog differs from that intended by the teacher, the student’s subsequent understanding of the target concept will probably be scientifically inappropriate. We believe that it is imperative that teacher and student hold a common view of the analog before analog-target mapping commences.

Thus, at Step 2, if the student visualises the analog in a different way to the teacher, is it any wonder that the student generates alternative conceptions? Teachers draw on a far richer knowledge base than do the students and there may be distinct cultural and socioeconomic differences between the teacher and the students.

Steps 3 and 4 may unite as a single step and our research indicates that as a teacher becomes proficient in the use of this teaching sequence, this does occur (Harrison, 1992). As relevant features of the analogy are identified (Step 3), they are often mapped immediately as the first of the shared attributes (Step 4). Our in-class observations showed that student mapping of the shared attributes cannot be taken for granted. Additional shared attributes that were not immediately apparent appeared as the analogy was discussed in class and, on several occasions, weaker students made valuable contributions to the mappings that had been overlooked by more able students.

Post-lesson interviews highlighted the value of examining the unshared attributes. Every analogy breaks down somewhere and many of the analogies employed in science are used for phenomena that are foreign to the student. It is unreasonable to expect novices to make expert judgments on structures or functions they cannot see or even visualise. Neither the teachers nor the students interviewed felt that the extra time spent delineating the unshared from the shared attributes was excessive even though the analogy sometimes occupied 15-20 minutes of the lesson. Students stated that because the teacher had identified the unshared attributes for them, they were much more comfortable with their understanding. It also is expected that many teachers will perform Steps 4 and 5 as a parallel exercise because as students propose analog-target mappings, shared and unshared attributes will emerge side-by-side.

The summary at Step 6 is necessary to articulate what has been found by carefully relating the familiar to the unfamiliar.

The Domino Analogy for Conduction of Heat in Solids

The account that follows describes a lesson with a mixed ability Year 8 class that was studying the topic Heat in which the teacher, Mrs Kay (not her real name), used the domino analogy. The students were familiar with the kinetic theory from their previous topic on Atomic Structure. The observed lesson was the third lesson on Heat and was dealing with methods of heat transmission, in particular, conduction. The lesson itself was audiotaped and the researchers' role was that of "observer as participant" (Merriam, 1988, p. 93). Following the lesson, the teacher was interviewed and during the next science lesson, students completed a worksheet on which they were asked to map as many of the shared and unshared attributes they could recall. Students were then selected for interview if they provided relatively full responses on the analogy mapping worksheet.

Figure 1: Books and dominoes represent respectively, particles and mobile electrons in a solid.

The audiotape of the lesson was transcribed verbatim and analysed to identify the six steps of the modified TWA model and the shared and unshared attributes mentioned by Mrs Kay and her students. All the interviews were similarly transcribed and Mrs Kay's interview was analysed to obtain her evaluation of the model's efficacy. The student interviews were scrutinised to assess the degree to which the selected students understood the analogy and to identify their mental image(s) of conduction of heat. The interpretations are discussed under the six steps of the modified TWA model as they apply to this analogy.

1. Introducing the Target Concept to be Learned

Mrs Kay introduced conduction by referring back to the previous lesson and by describing a commonplace phenomenon (which "feels the colder", the tap or the wooden bench) and by performing a simple experiment using two thermometers to measure the temperature of the tap and the wooden bench. This phase closed with her asserting, "would you all agree that the metal tap is transferring heat better"? .

2. Cueing Students' Memory to the Analogous Situation

Mrs Kay proposed the analogy by saying, "Now we have a little example here [row of books and a row of dominoes" - see Figure

1]. The visual impact of the line of identical books and the row of dominoes in front of the books quickly focussed the student's attention onto this analogy.

3. Identifying the Features of the Analog that are Relevant

Mrs Kay introduced the analogy by saying that, "a row of books and a row of dominoes is like particles in a solid." She followed with "these books, they're meant to represent the particles in a solid that are quite close together." It appears that Mrs Kay saw this comparison as being obvious and unambiguous. Her approach matches Gentner's criterion (1988, p. 76) that "access to memory is heavily influenced by surface similarity between [analog] and target ... in judging soundness, it is systematic structural overlap that counts." In-class observations, the lesson transcript and the student interviews suggest that the students understood this likeness and found it attractive.
For Mrs Kay, this was the appropriate time to check whether or not the students were familiar with the analog. During the post-lesson teacher interview, she indicated that the students' reaction at this stage encouraged her to further map the shared attributes: "I thought today the kids probably got the idea by seeing that without getting any more complex." Later in the interview, when the unshared attributes were being discussed, she maintained her confidence that the class were happy with the initial proposition by stating "I still think they got the general idea", and "this lot did seem certain ... they did seem to be with it." When the student interview responses to the specific propositions were discussed, it appears that, at this stage, the students were comfortable with this comparison.

4. Mapping the Similarities Between the Analog and the Target Concepts
The book/particles dominoes/free electrons analogy contained eight propositions relating to the conduction of heat. These propositions were analysed in the order in which they occurred. The student worksheets also provided information which is summarised in Table 21

Table 1: Incidence of shared and unshared attributes in Year 8 class that studied conduction of heat using the domino/book analogy (n = 22)

SHARED ATTRIBUTES	POSITIVE	NEGATIVE
Books in the line represent particles	21	1
Dominoes are like mobile electrons	22	

Books bumping is like particles bumping 2
Books too far apart is like a liquid 1
Only first book fell is like a gas 1
Size: dominoes<books::electrons<particles 3
Dominoes falling is like heat passing through 1
Books falling is like heat passing through 2

UNSHARED ATTRIBUTES

Books are similar in size to particles
19
Domino speed is similar to electron speed 14
3
Gas particles vibrate like solid particles 1
Books & dominoes stop after hitting suggests particles & electrons stop after hitting
1
Book speed is like particle vibration speed 1

On the student worksheet, spaces were provided for five shared and five unshared analog-target attribute mappings. For the first two spaces (of both shared and unshared attributes) either the analog or the target attribute was provided. For the following spaces, the student was required to provide the analog and the target attribute. In the following discussion, the items (i), (ii), etc, refer to the valid and invalid propositions contained in each analog-target link and are in the order they appeared in the lesson transcript unless otherwise stated.

(i) "books ... represent the particles in a solid which are quite close together."
The interviews revealed that the students recognised and readily accepted this initial premise. Referring to this initial link, the opening question in the interview asked each student "What do you think of that idea?" Each girl easily recalled the analogy expressing both interest and understanding at this superficial level. Comments further into the interviews revealed that each student understood that the books represent atoms and that atoms are closely packed in solids. Lizzy's comment was typical: "the dominoes were the electrons and the books were the particles, the atoms."
When discussing the fact that particles vibrate and disturb the ones next to them, Sally and Lizzy stated that

Mrs Kay made the point and I think the book does too, that the movement of the free electrons [dominoes] passes the heat better than the movement of the molecules. [Sally]

When she showed us the books and the dominoes, how they fell onto each other, it was because the vibrating atoms bump into

each other passing heat and energy, it was clear. [Lizzy]
None of the interview comments and only one worksheet statement was found that disconfirmed the proposition that "books are like particles."

(ii) "When we heat particles, [they] start to move and spread out the relationship between heat and motion in the following way: "it sort of gets heated up and moves a bit faster and it sort of it moves faster and then it is heated up."
While this was the only statement that mirrored the teacher's idea, the thread of the idea that getting hotter meant that the particles moved faster, ran through most of the interviews. However, the following comment by Sally suggests an alternative conception: "When they are heated, how they expand, they move when they're heated, they vibrate." Sally may have thought that the analogy was saying that the added heat starts the particle moving. Later when she was asked about insulators, she asserted that: "They don't move, the particles don't move so they can't conduct heat." This girl was the least talkative of all the interviewees and was the least sure of the four.

(iii) All particles move, when heat is added they move faster. Mrs Kay inferred this propositional statement when she said to the class, "I'm heating this end of the solid (pushes over first book)" which hits the next, making it move like transferring heat to the next particle. This idea that heat is analogous to motion was consistently evident throughout the interviews and the student worksheets. During the student interview, Tina, made a very perceptive remark when asked to describe the analogy.

Tina It's, it sort of got me thinking that they sort of stop after they move. So they move and they hit something and transfer the heat and they just stop where they lose the heat, sort of just passes through.
Int. Like the book is lying there still, once it's done its job?
Tina It's done its job and it stops.
Int. Do you think that's how it really works?
Tina No.
Int. How do you think it really works then?
Tina All the particles move around and they hit each other and they keep moving on so the heat transfers into other particles which keep moving and hitting the other ones and keep transferring the heat to everything.
Int. So if you have this long piece of copper wire, and you heat this end, what happens?
Tina It heats the next [particle] and the next one and the next one and it carries through.
Int. What about the one that was moving that did the bumping, is it still going to be moving?
Tina No. In a piece of copper wire it's not ...

Int So in a piece of copper wire, if you heat one up, it moves quickly, bumps something else, so it's not moving quickly?
Tina No. It still is, but the example shows that it's not.
Int. So you're saying to me - the example says it moves, then stops, but you know that it keeps moving?
Tina Yes.

Tina recognised this limitation in the analogy that, if you take the analogy literally, the particle starts, hits, stops. However, she could disregard this misconception, but the research did not determine whether or not other students were equally perceptive. This observation makes a powerful case for examining the unshared attributes, and especially, from the students' cognitive viewpoint.

(iv) The particles are further apart in the liquid phase.   This propositional statement emerged from the following comment made by Mrs Kay during the lesson. "A little bit further apart ... that was more like a liquid wasn't it?"
This proposition emanated from the failure of the first attempt to apply the domino effect to the line of books. The fact that the books were too far apart was seized upon to analogically show why liquids are poor conductors. Sally understood this point when she said: "like in liquids they're too far apart, like they hardly bump into each other, so it's difficult to conduct." Several students such as Lizzy, focussed upon gases which have even greater interparticle distances: "in the solid they pass heat better than in a gas because in a solid the atoms are very close together, so not as much heat can be passed through in gases."
(v) One book hitting the next is like conduction.   The statement by Mrs Kay that led to this propositional statement was, "all the particles are close enough to pass on the vibrations" and "now this way of transferring heat by particles passing on vibrations is called conduction."
This mechanism is the central issue in this analogy for conduction. The interviews demonstrated that each student had absorbed this idea. In describing this mechanism, three of the four girls produced over half a page of transcript each. The fourth girl, Tina, provided ten full lines of information. The following four excerpts from the student interviews show how these students understood the domino-effect analogy for conduction of heat in a solid:
When they vibrate they knock the next ones, and that vibrates too and it knocks the next one, and it vibrates as well, and in a solid [the atoms] pass heat better than in a gas ...   [Lizzy]

It makes the rest of [the atoms and electrons] move because one bumps into the other. [Sally]

The particles, they vibrate and ... pass the energy on ... when it bumps into the other ones. [Peta]

The first [particle] heated bumps the next one and then that one gets the heat, and the next gets it and so on. [Tina]
(vi) The books represent atoms and the dominoes represent free electrons. This propositional statement came from the following comments by Mrs Kay, "these books are our atoms here and these dominoes, these little ones, are meant to represent free electrons." The proposition that the dominoes represented the "free electrons in a metal" was also well received as evidenced by the following remarks.
The dominoes were the electrons and the books were the particles, the atoms ... [Lizzy]

Dominoes probably move faster because they're smaller ... there'd be more of them to the number of books ... electrons would move faster than the particles. [Tina]

(vii) Both electrons and atoms transfer heat energy. Mrs Kay had said that "free electrons also vibrate, so we've got a double way of passing on the vibrations." This propositional statement is important when discussing conduction in solids

because it explains why some solids (metals) are good conductors while others (wood, plastic) are not. The interviews again indicated that these two girls understood this idea.
Substances with many free electrons convey heat more faster than those that don't have free electrons. [Tina]

Int. Why are metals good conductors?
Tina They have free electrons which move faster than particles but do sort of the same thing ... there's more things doing it. [Peta]
The comment from Tina in (vi) above also supports the idea that
Free electrons, that's just in metals and they move all around the place because they're free. ... they're moving faster because they're smaller ... [Tina]

(viii) Because dominoes are smaller than books, free electrons are smaller than atoms. This propositional statement arose from seeing the model and the fact that Mrs Kay explicitly identified the books as being like atoms and the dominoes being like electrons throughout the lesson. Mrs Kay stated both before and after the lesson that this was her reason for choosing books and dominoes as the analogs. The relative size of atoms and electrons was not discussed in the lesson and this idea was encountered on only three of the student worksheets. Several

students mentioned this point during the interviews.
I thought that the electrons had to be smaller since, because all atoms have electrons inside them ... so I thought they must be smaller, I thought the dominoes were a good idea. [Lizzy]

But Tina interpreted the relative size of books and dominoes and suggested that there is less difference between electrons and atoms than there is between dominoes and books. This is evident from the following interview statement: "... a bit nearer in size maybe?"

One student identified an extra shared attribute not mentioned by Mrs Kay.
(ix) The speed of the particles. The line of dominoes fell over faster than the line of books showing that electrons transfer heat faster than particles. This similarity was recognised by Lizzy as evidenced by the following interview comment:

Dominoes will fall over a long time before the books. It is showing that a substance with many free electrons convey heat more faster than those that don't have free electrons. ... The dominoes fell faster than the books ... electrons move faster than the atoms.

5. Identify Analog-Target Links Where the Analogy Breaks Down
No invalid analog-target links were mentioned by Mrs Kay during the lesson, though unshared attributes were discussed at length during the post-lesson interview with Mrs Kay when she stated that
Yes, I could have talked about the unshared attributes a bit more. I probably should have said that the particles are obviously a lot smaller ... we have talked about that before ... about the structure of the atom. ... I think they ... know they're smaller, but probably I should have said, ... obviously the particles aren't this size. I know I didn't do the unshared attributes. But to me it seemed a quick little thing [the analogy], that it wasn't really worth it.

Nevertheless, the students identified three instances in which the analogy breaks down These unshared attributes were:

(i) The particles stop moving after they hit the particle next to them. When the book or domino fell over it ceased moving, thus particles and electrons stop once they have transferred energy to other particles. This difference was volunteered by two students during the interviews.
Int. Once the book had fallen over it was still. Do you

think that matches?
Liz No, I think they keep on vibrating, and just keep on moving. on heat, not what they did after they passed on the heat.

I thought they'd still keep vibrating, because after they bump into the other ones ... they'd be all round the place ... [Peta]

Tina's comment on this item is described fully in the discussion of propositional statement (iii) which says that "all particles move, when heat is added they move faster."

(ii) Size difference between books and electrons was inappropriate. This difference was given by Tina when she said that: "you need bigger books because the particles are much bigger than the electrons."

(iii) Free electrons are far superior to particles for transferring heat. The real difference is far greater than the model indicates. This generated a alternative conception for Sally because she was led, when discussing insulators, to say: "well solids don't have particles and like plastic, is not as good a conductor ..."

6. Summarise, Drawing Conclusions About the Target Concept

The conduction concept was rounded off by Mrs Kay saying: "So metals are the best, then solids, then liquids and gases are pretty poor."

Conclusions

This was the second lesson in which Mrs Kay used the modified TWA model to present an analogy in a systematic maner. At her first attempt she covered each of the six steps in a linear fashion but, as is evident above, she failed to overtly discuss the unshared attributes of the domino analogy. In reflecting upon her performance, Mrs Kay stated that "I had written [the model] down, but I hadn't really looked at it last night which I probably should have ... I should have looked at it, ... I could have talked about the unshared attributes a bit more."

Based on four lessons in which we observed Mrs Kay implimenting the modified TWA model, and from the student interview responses, it appears that three teacher actions are essential for effective teaching with analogies. These are, one, ensuring that the teacher and the students visualise the analog in the same way; two, developing the shared attributes to plausibly elucidate the target; and three, clearly identifying the unshared attributes for the students. When these three cognitive activities are performed in a manner that is intelligible, plausible and fruitful for the students, it is most likely that the resultant student understanding will be compatible with the teacher's expectations.

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