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TEACHING AND LEARNING WITH ANALOGIES

Friend or Foe?

1. TWO EDGED SWORDS

The *Friend or Foe* metaphor in the title raises timely questions about the value of analogies in science education. Science teachers and textbook writers differ widely in their enthusiasm for analogical explanations: some use many analogies (Harrison, 2001; Harrison & de Jong, 2004); others are wary because they cannot predict how their students or readers will interpret the analogies they use to teach science (Treagust, Duit, Joslin & Lindauer, 1992; Thiele & Treagust, 1994). This chapter therefore discusses the importance and role of analogies in the teaching and learning of science. It is now more than 10 years since Duit (1991) reviewed the literature on the use of analogies in science education; therefore, we examine new and old studies and ask, “what have we learned over the past decade about the pedagogical and epistemological value of science analogies?” and, “to whom are analogies most important: science practitioners, teachers or students?” The latter question is important because it asks “are analogies just excellent communication tools or can they generate new knowledge?” We begin our discussion by concentrating on the use of analogies in teaching and learning.

Much of the research to date has focused on how teachers understand and use analogies (e.g., Glynn, 1991; Treagust, Harrison & Venville, 1998), however, students’ interpretation of teaching analogies deserve equal attention (e.g., Gick & Holyoak, 1983; Dagher, 1995a). This problem raises a further question about analogies research; “Do students see, interpret and apply analogies in the way intended by teachers and textbook writers?” Studies into student understanding of analogies mostly concentrated on the knowledge developed by “good” or talkative students; but what do the majority of students understand when analogies are used to explain abstract and difficult ideas such as molecules, diffusion and plate tectonics?

Analogies have been called “two-edged swords” because the appropriate knowledge they generate is often accompanied by alternative conceptions. When people ‘receive’ analogies, they use their past knowledge, experiences and preferences to interpret the analogy so that it harmonises with their current personal

and social milieu. In modern terms, this is called *the personal construction of meaning*. Science classrooms are a common setting in which analogies are used to enhance concept learning; therefore, improving the way analogies are used in science education has important teaching and learning consequences.

2. MEANINGFUL LEARNING WITH ANALOGIES

When students study new concepts, meaningful learning proceeds when they find and visualise connections between a newly taught context and what they already know. This is especially important in inquiry learning where connections are built between familiar and non-intuitive science contexts. Inquiry includes the following: novel questions and problems are identified; activities are planned; students investigate the questions and problems; the teacher discusses the data and interpretations with the students; and the teacher asks questions, provides ‘need to know’ information and sometimes offers analogies. If the analogies are appropriate, they promote concept learning because they encourage students to build links between past familiar knowledge and experiences and new contexts and problems. Consider two examples.

Example 1. Harrison and de Jong (2004) provide an example of a socially generated student analogy. A Grade-12 teacher called Neil was explaining the conditions for chemical equilibrium. In answer to a student who asked “what do you mean by dynamic [equilibrium]?”, Neil used his “sugar in a tea-cup” analogy. In this analogy, a new molecule of sugar can dissolve only if a dissolved molecule first crystallises out of the saturated solution. As Neil concluded his story, a student called Mal interrupted with:

Mal: Is that happening when you’ve got like food in a pot and you’ve got a lid on, and when some evaporates at the same time, some is condensing and dropping down at the same time?

Neil: Yes ... it’s a closed system if I’ve got the lid on pretty tight? [St. Yeah ...] not completely closed, but it will do... Now, they tell you add this and that, simmer for 20 minutes with lid on. Why tell you to do that? Why leave the lid on?

St.: Liquid stays in the pot.

Neil: And the liquid’s got to stay in the pot, why?

St.: Cause otherwise it’ll all evaporate and everything will like go dry.

In the three lessons that we observed, Neil used nine analogies and the students contributed one! The lessons were highly interactive; yet the students still found it hard to generate scientifically relevant analogies despite understanding the concepts under discussion. When a student analogy arose, Neil capitalised on it and the students easily mapped the analogy as shown in later interviews. This study is typical and demonstrates that most analogies are teacher generated but, in conducive circumstances, students can generate effective analogies.

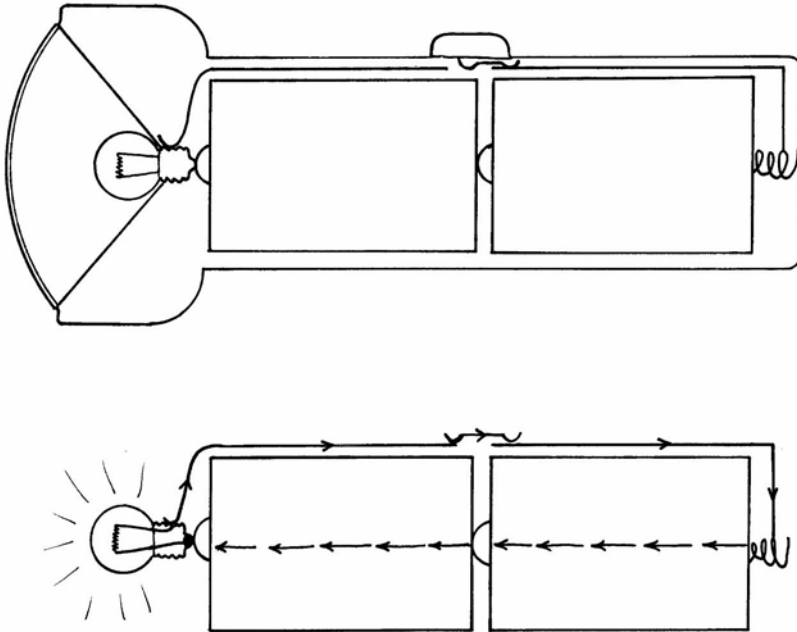


Figure 1a. Series circuit in a flashlight

Example 2. A Grade-9 teacher called Sally was investigating electric circuits. In a short time, Sally realised that her students thought that current is used up in the series circuit found in a flashlight (Figure 1a). This conclusion is reasonable because the light grows dim as the batteries run down. To explain current conservation in the circuit, she presented the continuous train analogy (Dupin & Johsua, 1989) (Figure 1b). The train (representing the current) is clearly conserved while the passengers (representing energy) move from Station 1 (energy in the battery) to Station 2 (energy converted to heat and light). When Sally used this analogy, she ‘gave up’ part way through the analogy when she realised that her version of the analogy taught the students that current changes speed (and intermittently stops) as the train loaded and alighted passengers. Despite a detailed rehearsal of the analogy using diagrams and a model train, Sally found that the analogy that worked well for other teachers, fell apart in her class. Sally was a perceptive teacher and realised that an alternative conception would result if she maintained the continuous train analogy. She stopped, aborted the analogy, and explained to her students what was going wrong with the analogy and reverted to a classical explanation of the difference between current and energy.

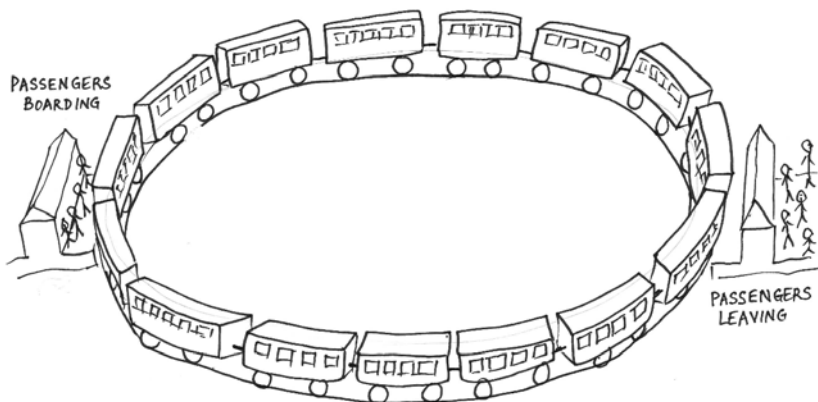


Figure 1b. Continuous train analogy shows that current is not consumed in a series circuit

The problem. Sally's quandary is highlighted by Zook (1991) who warns that teacher supplied analogies are easy for students to access but difficult for them to recite and map (in the above case Sally was like a student). Conversely, students find it difficult to generate their own analogies but, when they do create an analogy, they find it easy to map. This tension is important because most analogies are teacher or textbook supplied. Analogies are easy for some teachers to generate but hard for the students to map and apply. Student sourced analogies are rare and difficult to generate (Wong, 1993) but when they do arise, mapping is easy and meaningful learning follows (Cosgrove, 1995). It is rare for students to generate appropriate analogies that will not lead to alternative conceptions but they easily map the analogies that they do create in their investigations and discussions.

Most studies treat analogy generation as a student problem; however, we argue that many teachers are like students when it comes to analogy choice. The 'teacher acting like student' is demonstrated by their preference for the "water circuit analogy" for electric current (e.g., Hewitt, 1999, p.535). The water circuit analogy encourages the alternative conception that electricity is fluid-like and explains conclusions like electricity escapes from an unplugged socket and resistance is due to friction between the electrons and a cable's insulation (Champagne, Gunstone & Klopfer, 1985). One of the weaknesses of the water circuit analogy is the propensity of teachers to use it to explain all the features of an electric circuit. Multiple analogies are better with each analogy selected for the concept it explains best. Before we discuss multiple analogies, however, we need to more generally examine analogies in science.

3. ANALOGIES IN SCIENCE

Analogies and analogical models are popular in science and help scientists understand and communicate the intricacies, beauty and strangeness of the natural

world. Consider these examples: First, Stephen Hawking used at least 74 everyday analogies in *A brief history of time* to explain astrophysics and quantum ideas. To demonstrate that the universe is expanding equally in all directions, he says “the situation is rather like a balloon with a number of spots painted on it being steadily blown up” (p.45). He later muses that we could capture a black hole by “towing a large mass in front of it, rather like a carrot in front of a donkey” (p.115). Second, Robert Oppenheimer of atomic bomb fame claims that most of the significant advances in science used analogy as a thinking tool. He uses the history of science to show that scientific progress is aided by analogical thought and, for example, shows how analogy favoured the discovery of mesons. Third, Bronowski (1973) claims that imagining the workings of a clock helped Johannes Kepler (1571-1630) develop his ideas of planetary motion and fourth, Watson and Crick insisted that they arrived at the double helix structure of DNA by making analogical models that fitted their data. Finally, Peter Atkins’ (1995) book *The periodic kingdom* is one vast analogy. Other scientific discoveries that used analogical thinking are presented in Table 1.

Table 1. Scientific discoveries that used analogical thinking to advance science

Maxwell used water pressure in tubes to mathematically describe Faraday’s electric lines of force
Robert Boyle imagined elastic gas particles as moving coiled springs
Huygens used water waves to theorise that light was wavelike
Konrad Lorenz used analogy to explain streamlined motion in both birds and fish
Kekulé derived his idea for a benzene ring from an image of a snake biting its tail

Our specific study of the explanations used in science lessons began by searching for an exemplary science explanation (Treagust & Harrison, 2000). A model case was Richard Feynman’s first lecture—*Atoms in motion* (in *Six easy pieces*, Feynman, 1994). Analysis of this lecture showed that Feynman used 12 analogies to explain non-observable particle phenomena and five of these analogies are listed in Table 2.

Table 2. Five analogies used in Atoms in motion

paramecia are like "small football shaped things" (p.4)
molecules in water are moving "like a crowd at a football game" (p.4)
if an apple is magnified to the size of the earth, atoms in the apple will be as big as an apple (p. 5)
an atom hitting a moving piston is like a ping-pong ball hitting a moving paddle (p.8)
Brownian motion is like a game of push-ball (pp.19-20)

4. ANALOGIES IN SCIENCE EDUCATION

Analogies are promoted as successful science thinking tools by scientists and seen as problematic by the education research community (Dagher, 1995b; Duit, 1991). We now reflect on the process of analogy. Analogy can be a statement of proportionality or an application of process likenesses from one domain to another. Both are found in science teaching analogies. Statements of proportionality are best seen in surface similarities that could be called procedural analogies and, in their simplest mathematic form, involve deductions. A proportional analogy takes the form of $A:B::C:D$ and is evident in the example $3:6::5:10$. Any missing term can be deduced from the other three. A science example is the kinetic theory's depiction of atoms and molecules as perfectly elastic balls and a cell is like a box (the cell metaphor already conveys this surface structural similarity).

Process likenesses between domains are strongly relational and are found in analogies that build concept-process knowledge in new contexts. Such analogies use inductive reasoning to generate systematic or process knowledge in the new context. Inductive thinking resembles the effect a magnet has on an adjacent iron nail – the nail becomes a magnet so long as it remains in the strong magnetic field. Before exploring the “field” analogy, Carey's (1985) principle of inductive projection has relevance. In order to explain how young children understand the structure and function of one animal in terms of another, she demonstrated that 4-6 year-old children projected their knowledge of a prototypical animal (typically a dog or sheep) onto similar and dissimilar animals. Where the new animal was large, inductive projection was strong; when it was a snail or other invertebrate, the projection was weaker. Carey's research suggests that surface likenesses favour analogy identification and mapping but, as other research shows, only process analogy promotes deep thinking and conceptual understanding. These principles are important as we try to understand which analogies are easily recognised (they have obvious surface likenesses) and which analogies foster concept learning (they contain multiple process mappings).

The “magnetic field” analogy referred to above is a relational analogy [or is it a metaphoric analogy with specific entailments (Lakoff & Johnston, 1980)?]. Each electro-magnetic entity in a magnetic field affects and is affected by every other entity in the field and this explains why a nearby iron nail becomes a temporary magnet. This principle also applies to gravitational and electric fields. The electric field concept is the only functional way to explain how the second globe in a 2-globe series circuit influences the other globe and the cell(s) in the circuit. The field metaphor is like a sporting field. For example, in a football game, the addition or loss of a star player immediately affects all the players on both teams. The players, the context and the rules create a web (or field) of interactions. They affect and regulate each other all the time. The field concept is functional and relational and explains what cannot be explained in terms of isolated material objects. Indeed, field explanations can only be understood in process and relational terms. But analogies like the field concept demonstrate analogy's strengths and weaknesses. The explanatory power of the field metaphor is its ability to explain what no other method can do; its weakness lies in the inappropriate mappings that often emerge

and lead to the demotion of the field concept to an algorithmic mantra. Fields are often stated as the reason for force acting at a distance but they are rarely explained. Such is the elusiveness of certain analogies. But a closing comment on the field concept is warranted: Why do teachers and textbooks regularly introduce magnetic fields without qualification in Grade-8 science? The field concept is one of science's most relational analogies yet it is just stated, without explanation, to describe forces acting at a distance. (The field concept is likely a mystery to most teachers and students!) Faraday was perplexed by electromagnetic action at a distance and Maxwell needed to design complex mechanical analogical models using flowing water in pipes to make sense of this 'mysterious' phenomenon (Nersessian, 1992). However, research by Stockmayer and Treagust (1996) showed that many experts working with electricity (electricians, electrical engineers and lecturers of engineering and physics) held a field concept of electricity rather than a particle one.

This brief excursion into analogical thinking indicates the need for an explanatory classification of analogies..

5. A CLASSIFICATION SYSTEM FOR ANALOGIES

Curtis and Reigeluth (1984) examined 26 science textbooks and found that analogies could be classified into three types (see Figure 2). The most common type was the "simple analogy" where the writer said something like "an artery is like a hose" or "activation energy is like a hill". The grounds on which the comparison was based were not stated and the student was left to interpret *how* an artery is like a hose. They also found a second type of analogy where the grounds or conditions for the likeness were stated and they called these enriched analogies. Take the example "activation energy is like a hill because you have to add energy to the reacting substances to start the reaction". In dealing with metaphors, Lakoff and Johnston (1980) call these conditions "entailments". Enriching the analogy does more than tell the student under what conditions the analogy holds; it tells the student that the analogy is about processes, about dynamic functions and not limited to superficial structures. Indeed, the difference between a simple structural analogy and an enriched functional analogy is the addition of some form of causation; that is, a simple analogy is descriptive whereas an enriched analogy is more explanatory. The recognition and mapping problems that Zook (1989) described can be reduced if the teacher explicitly alerts students to the analogical conditions. Our research (Harrison & Treagust, 1993, 2000) demonstrated that explicating the conditions for each analogy reduced the incidence of alternative conceptions.

The final analogy type identified by Curtis and Reigeluth is the extended analogy. Extended analogies contain a mix of simple and enriched mappings or all the mappings are enriched analogies. The "eye is like a camera" analogy is an extended analogy. The grounds on which an "eye is like a camera" are stated in each case and there are multiple shared attributes in the analogy (and some limitations or unshared attributes).

Simple Analogy	ANALOG		TARGET
Enriched Analogy	ANALOG	grounds (limitations)	TARGET
Extended Analogies		grounds (limitations)	
	ANALOG	grounds (limitations)	TARGET
	ANALOG	grounds (limitations)	
	ANALOG	grounds (limitations)	
	ANALOG	grounds (limitations)	TARGET
	ANALOG	grounds (limitations)	

Figure 2. Simple analogy plus three levels of enrichment for textual analogies (adapted from Curtis & Reigeluth, 1984, p.111).

The eye is like a camera analogy is illustrated in Figure 3. This is a popular extended analogy; but as you peruse the analogy, think about this question: Is the eye an analogy for the camera or is the camera an analogy for the eye? Indeed, in the digital and video-camera age, has this analogy passed its use-by-date? We claim that outdated, teacher favourite and idiosyncratic analogies can be responsible for many an alternative conception!

The problem with one-analogy-teaches-all was introduced in the critique of the water circuit for a simple series circuit. There are excellent reasons for using multiple analogies when explaining abstract concepts like electricity, atom and molecules, biological systems (e.g., circulation and ecology) and there are problems. On the benefit side, a class of teenage students will present many different interests and levels of prior knowledge and experience. Presenting a menu of analogies as Neil did when explaining chemical equilibrium (nine analogies in three lessons – see Table 3) provides the students with epistemological and ontological choice. They can use the analogy(s) that makes most sense to them to explore the difficult concept. But multiple analogies have a downside – students who think that there is just one right answer to every problem feel confused and wonder, “what is this teacher trying to do to me!” Without help, multiple analogies often lead to multiple alternative conceptions and the recommendation for individual analogy presentation applies equally to multiple analogy explanations: it is crucial for the teacher to summarise the analogies and interrogate students’ understanding of the individual analogy and the collection of analogies. We cannot assume that students understand and appropriately map our analogies.

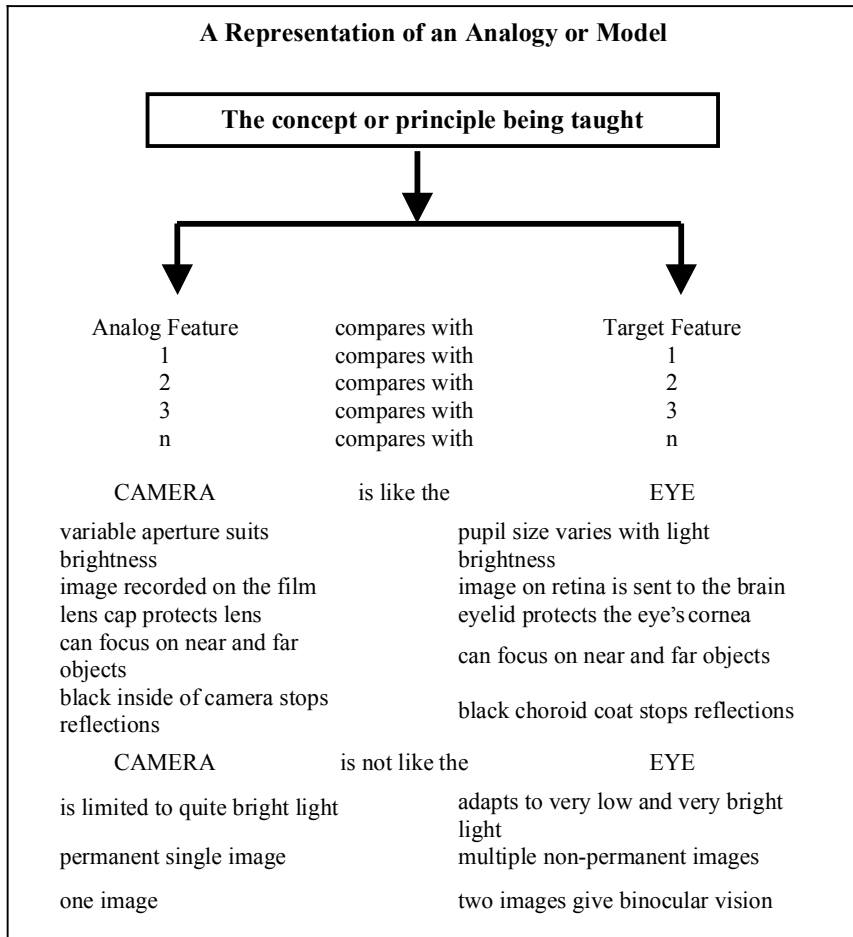


Figure 3. The camera is like an eye analogy

Electric circuits provide an excellent case for multiple analogies. Some of the analogies that can be used for current conservation include:

- A continuous train that travels a loop and picks up people at one station (the battery) and drops them off at another station (the globe). It is important to identify the train carriages as the current and the people as the energy.
- A bicycle's continuous chain transfers energy from the pedals on the gear wheel (battery) to the sprocket on the rear wheel (the globe). It is important to identify the likeness between the continuous chain and the wire carrying a continuous current.
- A conveyer belt picks up coal at the mine (the battery) and drops it into nearby railway wagons (globe).

- A role-play where a student collects jelly-beans from the teacher (battery) and walks around a circle of students (the circuit) giving jelly-beans to 3-4 students (these students are the globes).

Table 3. Neil's analogies in their order of appearance in the lessons on chemical equilibrium (see Harrison & de Jong, 2004)

<i>Analog (familiar situation)</i>	<i>Target (science concept)</i>
1. School dance – 500 boys, 500 girls in hall but only room for 250 couples to commit in the commitment room	Conditions for chemical equilibrium; couples committing and breaking up is continuous, rate committing = rate breaking up, and the hall is sealed
2. Up- and down-hill skier	Activation energy, energy input before energy output
3. Teacher with petrol and lighter	Teacher waving a lighter near a can of petrol illustrates the effect of adding activation energy – explosion!
4. Air flight including route details	Reaction mechanism, many steps produce the overall effect
5. Assembling a model aircraft	Reaction mechanism, many steps, some parallel like assembling two identical wings
6. Balancing on a see-saw	Physical equilibrium; force x distance balanced on each side
7. Being normal and insane	Physical equilibrium is like being mentally stable
8. Excess sugar in a teacup	Dynamic nature of equilibrium; cup sealed, rate dissolving = rate precipitating; process continuous, temperature dependent
9. Busy highway	Dynamic nature of equilibrium; rate cars entering = rate of cars leaving, collision rate is important

6. THE FAR GUIDE

Throughout this chapter we have warned that analogies are two-edged swords. When students are left to interpret analogies on their own, they can just as easily construct alternative conceptions as the desired scientific conception. All analogies break down somewhere and we demonstrated the alternative conceptions that can arise from misinterpretation of the water circuit for electric circuits and the eye is like a camera. All analogies have unshared attributes, they all break down somewhere and they usually break down sooner than later. This problem was well explained by Duit (1991) and Glynn (1991). Glynn therefore developed his six-step Teaching-With-Analogies (TWA) model and this model was evaluated by Harrison and Treagust (1993). Despite the apparent elegance of Glynn's model, teachers regularly forgot to implement one or more steps. This is understandable in a dynamic classroom setting with all the interruptions to which teachers and classes are prone. Based on their research with many schools, teachers and lessons, Treagust et al. (1998) proposed the Focus—Action—Reflection (FAR) guide. The FAR guide has three stages for the systematic presentation of analogies and resembles the planning phases of expert teaching and the action research model. The FAR guide is illustrated in Figure 4. When teachers present analogies using the FAR guide

framework, it is our experience that students' scientific understanding is enhanced and the variety and frequency of alternative conceptions are diminished (Harrison & Treagust, 2000).

The FAR Guide for Teaching with Analogies and Models

Pre-Lesson FOCUS	
CONCEPT	Is the concept difficult, unfamiliar or abstract?
STUDENTS	What ideas do the students already have about the concept?
EXPERIENCE	What familiar experiences do students have that I can use?
In-Lesson ACTION	
	Check student familiarity with the analog
LIKES (mapping)	Discuss ways in which the analog is like the target Are the ideas surface features or deep relations?
UNLIKES (mapping)	Discuss ways in which the analog is unlike the target
Post-Lesson REFLECTION	
CONCLUSIONS	Was the analogy clear and useful, or confusing
IMPROVEMENTS	What changes are needed for the following lesson? What changes are needed next time I use this analogy?

Figure 4. The FAR guide or Focus—Action—Reflection approach for teaching with analogies (Treagust et al., 1998)

7. ANALOGIES – COMMUNICATION OR INQUIRY TOOLS?

Analogical knowledge is not strictly empirical knowledge and this raises several problems. When we use analogies, the analog—target similarities, called mappings, are classified as shared attributes (positive analogy) or unshared attributes (negative analogy). Mary Hesse (1963) proposed a third mapping called the neutral analogy. Neutral analogy can be a source of possible new relationships that raise questions and stimulate new research. But how do scientists judge the intelligibility, credibility and fruitfulness of the neutral analogy? Scientists who understand the positive and negative attributes of analogies will probably use this knowledge to evaluate the neutral analogy. But how was the now accepted positive analogy agreed on in the first place? And, if the new relationship suggested by the neutral analogy is useful (like Kekulé's snake biting its tail), is it new knowledge or is it just a better way of organising data and ideas already held in memory? And when does the scientific community accept discovery generated by analogy? Furthermore, when the

theoretical edifice suggested by analogy is established by theory and experiment, is the analogy retained by scientists or only by educators? These questions suggest that there may be significant differences between the way scientists and teachers judge analogical knowledge.

The history of science also shows that a long time may intervene between the genesis of an analogical idea and the acceptance of the resulting theory. Bronowski claims that Kepler's ideas of planetary motion were suggested by the working of a clock, but many years separated the wheels revolving in wheels analogy and the acceptance of Kepler's laws.

So, who decides when an analogy becomes credible and fruitful and what operational criteria are used to make these decisions? In science, new knowledge is unique and deserves to be called a discovery; however, in science education knowledge that is new from the student's viewpoint can almost be axiomatic for the teacher. The philosophical distinction between research knowledge and education knowledge is important because many scientists also are university teachers. Scientists may wear different epistemological or philosophical hats when teaching and when researching science with analogies.

We propose that analogical knowledge may be better described as a thinking tool for scientists because analogy does not actually qualify as empirical knowledge. Indeed, Cosgrove (1995) demonstrated that analogy is an excellent thinking tool in school science provided the teacher understands the concept being taught and can guide his or her students in the inquiry process. As Cosgrove shows, the best analogies are student generated and in the absence of student analogies, teacher analogies that are multiple and presented in a format like the FAR guide can enhance learning. As we have argued in this chapter, analogy is a powerful way to think, construct ideas and test new knowledge. But someone in the process must know and understand the desired learning outcomes; otherwise, the likely result will be more alternative conceptions.

8. CONCLUSION

As we have illustrated in this chapter, on balance analogies are a friend to teachers and students alike but as we emphasise, analogies can be double-edged swords. In order that analogies are used as an effective tool in a science teacher's repertoire, knowledge about their pedagogical function is essential.

In its most elementary form, science teachers' knowledge about analogies should include:

- the suitability of the analog to the target for the student audience and the extent of teacher-directed or student-generated mapping needed to understand the target concept;
- an understanding that an analogy does not provide learners with all facets of the target concept and that multiple analogies can better achieve this goal;
- an appreciation that not all learners are comfortable with multiple analogies because the epistemological orientation of some is to expect a single explanation for a phenomenon.

Additional understanding of how analogies can be optimally used in class can be derived from the history of scientific discovery and from accounts of the ways experienced science teachers use analogies. We do not wish to claim that analogies used in science classrooms will necessarily improve both science teaching and learning. Still, research has compellingly demonstrated that, when used effectively, analogies are a valuable pedagogical tool in teachers' repertoires and this enhancement of practice is our aim in writing this chapter.

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