

5.1 Making science concepts meaningful to students: teaching with analogies

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1 Introduction

Science-education research studies and science teachers' classroom experiences have shown that analogies, when used properly, can help make science concepts meaningful to students. This chapter explains what analogies are, how analogies foster learning and interest, and what form analogies should take to be effective. A research-based model for teaching with analogies is described: It provides guidelines for the use of analogies in science classrooms, textbooks, and web-based science instruction.

2 Analogies, science, and science teaching

Throughout history, analogies have played an important role in scientific discoveries, not as proof, but as inspiration. Analogies have also played an important role in explaining those discoveries (Kaiser, 1989). For example, Johannes Kepler, the famous seventeenth-century astronomer, wrote: *"I especially love analogies, my most faithful masters, acquainted with all the secrets of nature"* (cited in Vickers, 1984, p. 149). Kepler, who discovered laws of planetary motion, used analogies to help explain his discoveries: *"I am much occupied with the investigation of the physical causes. My aim in this is to show that the celestial machine is to be likened not to a divine organism but rather to a clockwork"* (cited in Holton, 1973, p. 72).

Steven Chu, who received a Nobel Prize in physics in 1997, used analogies to discover and explain his method of slowing down atoms with laser light. Chu calls his laser-light method "optical molasses" and explains it in this way: *When I was making a back-of-the-envelope calculation of how long the molasses [i.e., laser light] would keep the atoms in this region, I was thinking of a way to simulate this by computer, and I thought, "Well, you really don't need a computer simulation, because you can make an analogy to Brownian motion." The situation is very similar to Brownian motion where you have a dust particle and you put it in a fluid. As the atoms hit against this dust particle it starts to jostle around, and the fluctuations in the number of atoms that hit from the left and the right actually make the dust particle move. But the fluid dampens its motion; once it starts to move it hits viscosity in the fluid and wants to slow down. It's exactly the same in optical molasses, only it's a fluid of photons from the laser that creates the dampening. If the atoms want to move in the fluid they slow down, and it looks exactly like Brownian motion. (interview by May, 1998)*

Science teachers, like scientists, frequently use analogies to explain concepts to students (James & Scharmann, 2007). The analogies serve as initial models, or simple representations, of science concepts. The teachers frequently preface their explanations with expressions, such as, “It’s just like,” “Just as,” “Similarly,” and “Likewise.” These expressions are all ways of saying to students, “Let me give you an analogy.”

Analogies are double-edged swords: They can foster understanding, but they can also lead to misconceptions. As Duit, Roth, Komorek, and Wilbers (2001) explain:

A growing body of research shows that analogies may be powerful tools for guiding students from their pre-instructional conceptions towards science concepts. But it has also become apparent that analogies may deeply mislead students’ learning processes. Conceptual change, to put it into other words, may be both supported and hampered by the same analogy. (p. 283)

Effective analogy use fosters understanding and avoids misconceptions (Duit & Glynn, 1992, 1995). In order to use analogies effectively, it is important to understand exactly what an analogy is, how it can help learning, and what kind of analogy is best. In the following sections, these topics are addressed.

3 What is an analogy?

An analogy is a comparison of the similarities of two concepts. The familiar concept is called the analog and the unfamiliar one the *target*. Both the analog and the target have *features* (also called *attributes*). If the analog and the target share similar features, an analogy can be drawn between them. A systematic comparison, verbally or visually, between the features of the analog and target is called a *mapping*. A conceptual representation of an analogy, with its constituent parts, appears in Figure 1. An example of an analogy drawn between a water circuit and an electric circuit appears in Figures 2 and 3.

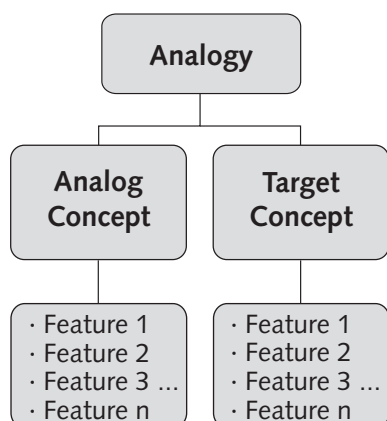


Figure 1: A conceptual representation of an analogy, with its constituent parts.

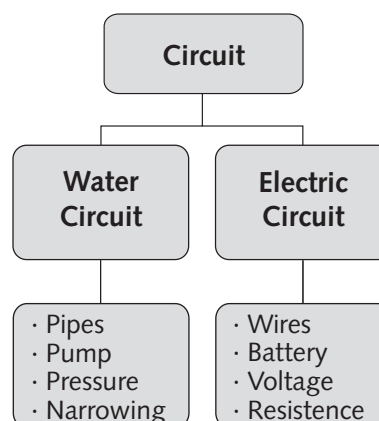


Figure 2: A conceptual representation of a water-electric circuit analogy.

Analogical reasoning can occur between conceptual domains and within a conceptual domain. Between the domains of physics and biology, for example, an analogy can be drawn between a camera and the human eye. Within the domain of physics, for example, an analogy can be drawn between the flow of water and the flow of electricity.

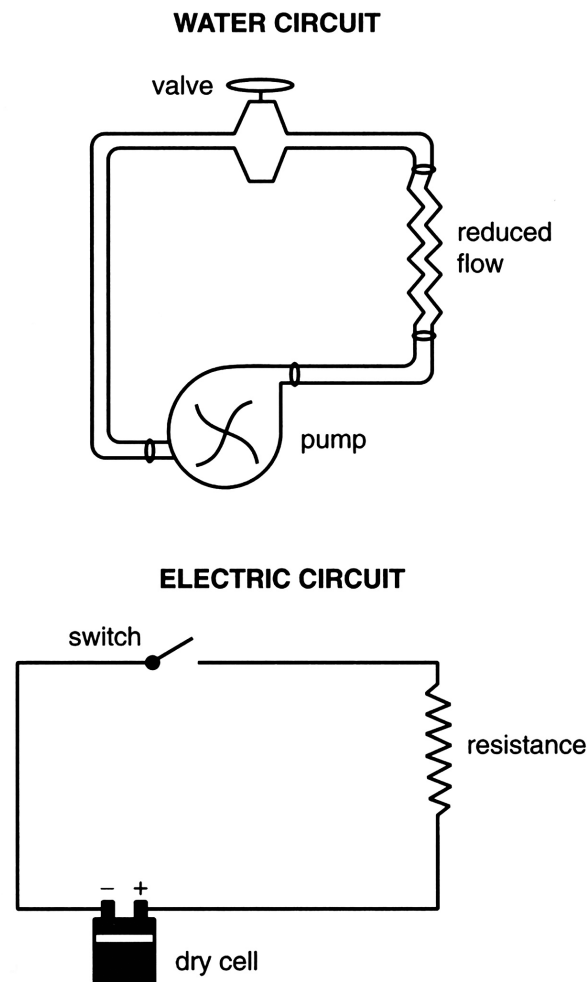


Figure 3: A water-circuit diagram and an electric-circuit diagram.

4 How do analogies help learning?

The analogies used in classrooms, textbooks, and web-based instruction should be designed to promote *elaboration*, the cognitive process of constructing relations between what is already known and what is new (Glynn & Duit, 1995). Elaboration can be defined more precisely as “any enhancement of information which clarifies or specifies the relationship between information to-be-learned and related information, i.e., a learner’s prior knowl-

edge and experience or contiguously presented information” (Hamilton, 1997, p. 299). Elaboration can be activated by questions, objectives, personal examples, and other strategies, but analogies seem to be particularly appropriate because they can provide the rich, familiar contexts that successful elaboration requires.

Elaboration plays a critical role in a constructivist framework for learning science. In this framework, students learn progressively more sophisticated mental models of science concepts. Often, these concepts represent complex, hard-to-visualize systems with interacting parts: An atom, a cell, photosynthesis, an electric circuit, and an ecosystem are all examples. Often, such concepts are introduced to students when they are about 10 years of age, and then elaborated in subsequent grades, technical schools, and college. Familiar analogs (e.g., a factory) often serve as early mental models that students can use to form limited, but meaningful, understandings of complex target concepts (e.g., a cell). The analogy paves the way for the expansion of the target concept.

5 What kind of analogy is best?

One characteristic of research findings on the instructional use of analogies has been, unfortunately, the inconsistency of the analogies’ effectiveness: Sometimes analogies enhance learning, and sometimes not (Glynn & Takahashi, 1998). This inconsistency has been due to weak operational definitions of analogies, to constructions of analogies that have failed to map analog features systematically onto target features, and to analogies that have largely ignored the important role that visual imagery can play in the learning process.

Instructional analogies are sometimes limited to simple assertions, such as “A cell is like a factory,” without explaining the analogy. These assertions, or *simple analogies*, do not provide the instructional scaffolding that many learners need, particularly in the initial stages of learning a concept.

A much better mechanism for providing instructional scaffolding is an *elaborate analogy*: “In an elaborate analogy, analog features are systematically mapped onto target features, verbal and imagery processes are active, and these processes mutually support one another” (Glynn & Takahashi, 1998, p. 1130). Elaborate analogies provide a rich, situated context for learning. By systematically mapping verbal and visual features of analog concepts onto those of target concepts, analogies can facilitate the cognitive process of elaboration. Elaborate analogies have been found to increase students’ learning of target concepts and their interest in the concepts (Paris & Glynn, 2004).

6 Science teachers’ use of analogies

Observational studies that have been conducted of science teachers at all grade levels indicate that they frequently use analogies when explaining fundamentally important concepts.

For example, Ms. Karen Stein (a pseudonym) recently taught Coulomb's law of electrical force to her class of 14- and 15-year-old students. When introducing this law to her students in a lesson on electricity, Ms. Stein said:

In the 16th century, Benjamin Franklin did many experiments with electrical phenomena, and he drew on analogies to explain them. In Franklin's view, an object acquired an electric charge by transferring an "electric fluid" that was present in all matter. According to him, when two materials, such as glass and silk, were rubbed together, some electric fluid passed from one into the other. One material then had an excess of fluid, while the other had a deficiency. The excess resulted in one type of charge, called "positive" by Franklin, while the deficiency resulted in another type of "negative" charge.

Joseph Priestley, a friend and colleague of Franklin's, took Franklin's ideas about electricity a step further. Priestley proposed a law of electrical force analogous to Newton's law of gravitational force. The law of electrical force was experimentally tested and refined by Charles Coulomb, and the law bears his name.

Think back to the unit we covered awhile ago on gravity and Newton's law of gravitation. In Newton's law, the gravitational force between two objects is proportional to the product of their masses and inversely proportional to the square of the distance between those two objects. I'm showing Newton's law on the screen in the front (see Figure 4). Newton's law is on the left side. As you can see, the law contains a constant, G , which is the universal gravitational constant.

Now look at the right side of the screen where Coulomb's law of electrical force is displayed. Notice that the electrical force between any two objects has a similar inverse-square relationship with distance. In Coulomb's law, when objects or charged particles are small in relation to the distance between them, then the electrical force is proportional to the product of the charges and inversely proportional to the square of the distance between the charged particles. As you can see, Coulomb's law also has a proportionality constant, k .

So, Newton's law of gravitation is analogous to Coulomb's law of electrical force. Both are inverse-square laws. And both have constants. But, although the laws are similar, there are important differences between them. For example, m represents the mass of an object and q represents the charge of a particle. And, although both laws have constants, the G in Newton's law is a very small number, whereas the k in Coulomb's law is a very large number. Yet another difference is that gravitational force only attracts, while electrical force attracts when charges are different but repels when they are similar.

In the preceding lesson, Ms. Stein was using the Teaching-With-Analogies Model (Glynn, 2004), which she had learned in a professional-development workshop conducted for the teachers in her school system. Before she learned the Model, she used analogies, but not strategically, and she was frequently unaware that she was even using analogies. Reflecting on her pre-workshop use of analogies, she said: "I guess I used analogies, but I didn't think much about them. I guess I did it automatically, especially when students weren't catching on."

It is risky to use analogies without thinking about them. If used effectively, they can enhance learning by building conceptual bridges between old and new knowledge; if used ineffectively, they can hinder learning by causing misconceptions. Knowing how to use analogies effectively is an important part of teachers' *pedagogical content knowledge* (Gess-Newsome, 1999).

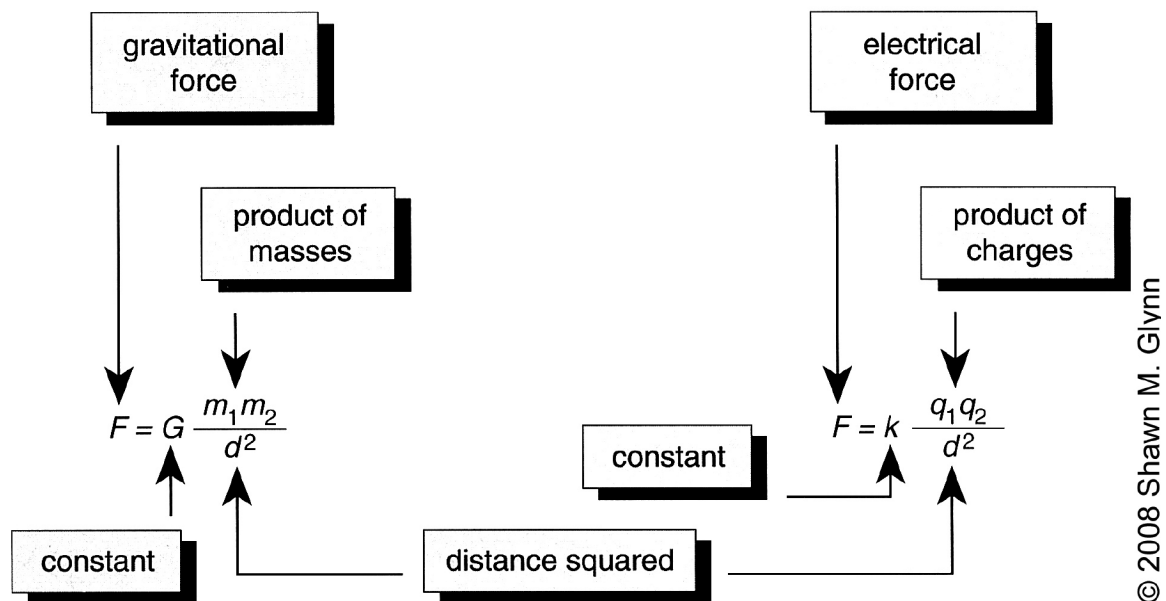


Figure 4: An analogy between two inverse-square laws: Newton's law of gravitation and Coulomb's law of electrical force.

7 Teaching-With-Analogies Model

The Teaching-With-Analogies Model (Glynn, 2004, 2007) is based on cognitive task analyses of lessons, textbooks, and websites. In both formal experiments and classroom settings, the use of the model has been found to increase students' learning and interest in science concepts (Glynn, Duit, & Thiele, 1995; Paris & Glynn, 2004). When Ms. Stein used the analogy between Newton's law of gravitational force and Coulomb's law of electrical force, she followed the six steps in the model:

1. Introduce the target concept, Coulomb's law of electrical force, to students.
2. Remind students of what they know of the analog concept, Newton's law of gravitational force.
3. Identify relevant features of Coulomb's and Newton's laws.
4. Connect (map) the similar features of the laws.
5. Indicate where the analogy between the laws breaks down.
6. Draw conclusions about the laws.

To help her students think about the analogy, Ms. Stein showed them Figure 4. She also warned her students, “This analogy between Coulomb’s and Newton’s laws, like all analogies, breaks down in a lot of places,” and pointed out how the analogy breaks down, such as gravitational force only attracts, while electrical force attracts or repels.

One implication of the Teaching-With-Analogies Model is that teachers should try to select analogs that share many similar features with the target concept. In general, the more features shared, the better the analogy. Another implication is that teachers should verify that students have not formed misconceptions. One way to do this is to ask focused questions about features that are not shared between the analog and the target concept.

Ms. Stein helped her students draw important conclusions about Coulomb’s law of electrical force and Newton’s law of gravitational force. For example, to help them understand that the constant, G , in Newton’s law was a small number and the constant, k , in Coulomb’s law was a large number, she explained “This means that the gravitational force between two 1-kilogram masses would be tiny, whereas the electrical force between two 1-coulomb charges would be large.” She also explained “The primary force between the planets and the sun is gravity, which attracts only – any electrical forces between them are balanced out because objects usually have equal numbers of electrons and protons. When we are talking about atoms and molecules, however, that is not always the case. Electrical forces play a much more important role than gravity at atomic and molecular levels.”

Finally, Ms. Stein wanted to spark her students’ imaginations and encourage them to think analogically about science concepts. To do this, she told her students that the similarities between Newton’s and Coulomb’s laws have inspired many scientists, such as Albert Einstein, to search for a “unified field theory,” which unifies electrical and gravitational forces. She said that scientists have not yet unified gravity with other forces, but perhaps one of her students might someday do this.

8 Analogies and web-based science instruction

Analogies play an important role in science instruction in all forms of media, such as textbooks and web-based science instruction. The role of analogies in textbook instruction has been examined in many studies (for reviews, see Duit, 1991; Paris & Glynn, 2004), but the role of analogies in web-based science instruction has been studied little because this medium is so new.

Because web-based science instruction is growing exponentially, and because its developers want to make it as effective as possible, the strategic use of analogies is receiving increased attention. For example, *The Guiding Principles for Distance Teaching and Learning* (American Distance Education Consortium, 2007), which are used to evaluate web-based instruction, emphasize the role of analogies: “Learning by doing, analogy, and assimilation are increasingly important pedagogical forms. Where possible, learning outcomes should relate to real-life experiences through simulation and application.”

Web-based science instruction refers here to science teaching and learning processes mediated by a web browser, operating from the Internet. Web-based science instruction has enormous potential for complementing and enriching traditional science instruction (Herrington, Reeves, Oliver, & Woo, 2004; Kahn, 2001; Mayer et al., 2006). Incorporating web-based science instruction into traditional science curricula has already been shown to increase students' motivation and achievement (Bodzin & Cates, 2002; Riffell & Sibley, 2005).

When web-based science instruction has features such as audio, video, animated GIF images, interactivity, and hyperlinks, it is roughly analogous to the instruction of a science teacher, such as Karen Stein. But this analogy, like any analogy, breaks down in places. Karen is more adaptive and intuitive than contemporary web-based science instruction, yet her interactivity is slower than that of a fast web connection.

Elaborate analogies are often used on science education websites to explain concepts, using various combinations of text, audio, video, animation, interactivity, and hyperlinks. For example, the website of the Genetic Science Learning Center of the University of Utah (<http://learn.genetics.utah.edu/units/stemcells/whatissc/>) includes a unit on stem cells, a complicated and controversial topic. An analogy compares a stem cell with a "stem cell guy," an animated cartoon-like actor who dances on a stage and divides into two cells. Learners are informed:

Like actors awaiting a casting call, stem cells wait for signals to tell them what to become. Stem cell guy has a lot of potential — he can become many different types of cells. But until he receives a signal, he must wait patiently and divide slowly. When stem cell guy receives a signal, he begins to differentiate, or gradually change into his destined cell type.

The stem cell guy analogy is not only animated, but interactive as well. Students can select what kind of cell they want stem cell guy to be. They can click and drag him into a "differentiation phone booth" and dial a number on the telephone to differentiate him into the cell of their choice, such as a skin cell, bone cell, or red blood cell. If they dial, for instance, a skin cell, then they learn about skin cells and view animations about the role that stem cell guy plays as a skin cell. The use of good text, audio, video, animation, interactivity, and within-site hyperlinks makes the stem cell analogy an engaging one. It is also valid one, given that it is designed for "non-research audiences." The use of the analogy is generally consistent with the Teaching-With-Analogies Model, with one exception: Little attention is given to where the analogy breaks down. One example of this is the statement, "Like actors awaiting a casting call, stem cells wait for signals to tell them what to become." At this point the analogy breaks down: Actors await casting calls from directors or producers, but what is the source of a stem cell's signal? This is not explained, and a misconception could arise. To avoid a misconception, students should be informed that signals inside and outside cells trigger differentiation. The inside signals are controlled by a cell's genes, while the outside signals include chemicals secreted by other cells, physical contact with other cells, and certain molecules.

The website of Beyond Books® (<http://www.beyondbooks.com/lif71/4a.asp>) includes science units for teachers to use with middle and high school students. In the unit The Cell: Down to Basics, a “busy factory” analogy is used to explain cell parts. The analogy compares the cell to a factory: “A cell can be thought of as a ‘factory’, with different departments each performing specialized tasks.” Cell membranes are depicted as swinging gates – clicking on these hyperlinked gates takes one to a related website, which provides more information on cell membranes. Likewise, the endoplasmic reticulum is depicted as a moving factory conveyor belt – clicking on it takes one to another related website.

The text in the unit is consistent with the Teaching-With-Analogies Model, including an indication of where the analogy breaks down:

With the exception of chloroplasts, all of the parts of the cell examined so far can be found in all cells. But now, as the discussion turns to more specialized organelles, the factory analogy will no longer apply. As cells become more specialized, they may contain organelles that are not common to all cells. Since they are not common to all cells, they are not necessary for all factories.

The students’ understanding of cell organelles and their functions is verified by means of interactive study questions, practice quizzes, key terms, and games. The text content is good and the analogy is animated, interactive, and hyperlinked; however, the implementation of these technical features should be updated.

Some other examples of science education websites using elaborate analogies include the following:

British Broadcasting Corporation and The Open University, Cell City
<http://www.open2.net/science/cellcity/>

Georgia State University, Department of Physics and Astronomy, Water Circuit Analogy to Electrical Circuit
<http://hyperphysics.phy-astr.gsu.edu/hbase/electric/watcir.html>

Indiana University, Office of Science Outreach, Enzyme reactions
<http://www.indiana.edu/~oso/animations/An6.html>

Purdue University, Genomics Analogy Model for Educators
<http://www.entm.purdue.edu/extensiongenomics/GAME/lesson3.html>

The Association for Science Education, Electricity Analogy
<http://sycd.co.uk/electricity-analogy/>

The Audio Education Resources Site, More About Waves: The Water Analogy
http://www.audioed.com.au/learnOL_demo/LOLdemo4.html

University of California at Los Angeles, Division of Astronomy and Astrophysics, Balloon Analogy in Cosmology
<http://www.astro.ucla.edu/~wright/balloon0.html>

9 Guidelines for designing analogies in web-based science instruction

Six guidelines should be kept in mind when designing elaborate science analogies. These guidelines are discussed here with a focus on web-based science instruction, but they also apply to other forms of media.

(1) Designers should take into account the characteristics of the target concept. If the concept is relatively simple and straightforward, an elaborate analogy might be unnecessary. Elaborate analogies have been found to enhance learning when the target concepts are complex and represent hard-to-visualize systems with interacting parts (Glynn & Takahashi, 1998). In combination with web-based animation, interactivity, and hyperlinks – features that have also been found to enhance learning – elaborate analogies have the potential to strongly enhance learning, provided that the features interact without increasing cognitive load (Bodemer, Ploetzner, Feuerlein, & Spada, 2004; Ploetzner & Loweb, 2004).

(2) Designers should take into account the characteristics of the analog concept. A good analog is one with which the students are already familiar, so it does not have to be taught from scratch, it just needs to be reviewed by means of hyperlinked websites. Another characteristic of a good analog is that it shares many features with a target concept, rather than just a few features.

(3) Designers should follow the steps in the Teaching-With-Analogies Model to introduce a target concept, suggest a good analog, identify similar features of the analog and target, visually map these features, indicate where the similarities break down, and draw conclusions about the target. Following these steps will help students to transfer relevant knowledge from the analog to the target and to draw valid conclusions about the target.

(4) Designers should hyperlink features of elaborate analogies to related bodies of knowledge. Creating hyperlinks, within the website and to other websites, simulates the exemplary science teacher's use of supplementary resources to enrich students' learning. Because students vary in their relevant background knowledge, designers should link to a variety of resources that are relevant, accurate, and authentic.

(5) Designers should animate elaborate analogies to ensure that they engage students' interest and promote understanding. Animation can help students to visualize the dynamics of processes (e.g., mitosis, photosynthesis, metamorphosis, oxidation, and erosion) by depicting temporal or causal sequences and the transitions that occur between stages and states.

(6) Designers should make elaborate analogies interactive to simulate the actions that exemplary teachers perform when using analogies. Students should be able to interact with components of the analogies by selecting embedded links. Actions such as questions, prompts, suggestions, and feedback should be incorporated into a hyperlinked, database-driven website that gathers information from students, displays it, and provides them with evaluations of their understanding.

10 Conclusion

As Duit et al. (2001) noted, “Analogical reasoning is a key feature of learning processes within a constructivist perspective: Every learning process includes a search for similarities between what is already known and the new, the familiar and the unfamiliar” (p. 285). Science teachers should support students’ learning by using analogies effectively. The steps in the Teaching-With-Analogies Model describe how to do this. Carefully crafted elaborate analogies can help students understand science concepts that represent complex, hard-to-visualize systems with interacting parts. Analogies can also increase students’ interest in these concepts. Carefully crafted, elaborate science analogies can help students build conceptual bridges between what they already know and what they are setting out to learn. Just like scientists such as Johannes Kepler and Steven Chu, science teachers should use analogies as pedagogical tools when explaining important concepts in science.

Acknowledgement

I wish to acknowledge a debt of gratitude I owe to Professor Dr. Reinders Duit – mentor, collaborator, and friend – who has contributed immensely to my understanding of the role of analogical thinking in the teaching and learning of science. It has been a great privilege to work with Professor Duit, an international leader in the field of science education.

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