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ABSTRACT

This paper describes the role of analogy in science instruction and presents new research on the Teaching-With-Analogies model. After an introductory section, the paper discuses learning science meaningfully, including constructing relations, strategies for learning conceptual relations, the definition of analogy, effectiveness of analogies, and misconceptions caused by analogies. The model described in the paper began with a task analysis of 43 middle school, high school, and college textbooks to identify how the textbook authors used analogies to explain new concepts. The paper notes that the task analysis was supplemented by a study of 10 exemplary middle school science teachers. The model described in the paper provides guidelines for constructing analogies systematically and using them strategically during science instruction to explain important concepts in ways that are meaningful to students. The paper shows how exemplary teachers and authors construct effective analogies to help students build on their own relevant knowledge by activating, transferring, and applying it to new knowledge acquired from textbooks. Contains 44 references, 2 tables of data, and 4 figures illustrating aspects of various analogies. (RS)

Teaching Science With Analogies

A Strategy for Teachers and Textbook Authors

Shawn M. Glynn
University of Georgia

NRRC National Reading Research Center

READING RESEARCH REPORT NO. 15
Spring 1994

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About the National Reading Research Center

The National Reading Research Center (NRRC) is funded by the Office of Educational Research and Improvement of the U.S. Department of Education to conduct research on reading and reading instruction. The NRRC is operated by a consortium of the University of Georgia and the University of Maryland College Park in collaboration with researchers at several institutions nationwide.

The NRRC's mission is to discover and document those conditions in homes, schools, and communities that encourage children to become skilled, enthusiastic, lifelong readers. NRRC researchers are committed to advancing the development of instructional programs sensitive to the cognitive, sociocultural, and motivational factors that affect children's success in reading. NRRC researchers from a variety of disciplines conduct studies with teachers and students from widely diverse cultural and socioeconomic backgrounds in prekindergarten through grade 12 classrooms. Research projects deal with the influence of family and family-school interactions on the development of literacy; the interaction of sociocultural factors and motivation to read; the impact of literature-based reading programs on reading achievement; the effects of reading strategies instruction on comprehension and critical thinking in literature, science, and history; the influence of innovative group participation structures on motivation and learning; the potential of computer technology to enhance literacy; and the development of methods and standards for alternative literacy assessments.

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Teaching Science With Analogy: A Strategy for Teachers and Textbook Authors

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Abstract. The author describes the role of analogy in instruction and presents new research on the Teaching-With-Analogies Model. This model is being developed from studies of exemplary teachers and textbooks; it provides guidelines for constructing analogies systematically and using them strategically during science instruction to explain important concepts in ways that are meaningful to students. The model shows how exemplary teachers and authors construct effective analogies to help students build on their own relevant knowledge by activating, transferring, and applying it to new knowledge acquired from textbooks.

Many of Galileo Galilei's (1564–1642) colleagues believed that the earth is standing still, not rotating on its own axis. Galileo could not accept this view. In an effort to convince Galileo, his colleagues argued that if the earth were rotating on its axis, a rock dropped from a tower would not land directly at the foot of the tower. They reasoned that if the earth were rotating, the tower would continue to move while the rock was falling through the air, with the result that the rock would hit the ground far away from the tower's foot. Since this obviously doesn't happen — the dropped rock actually lands directly at the tower's foot — the colleagues concluded that the tower and the earth could not be moving. The colleagues saw no reason to change their belief that the earth and the tower connected to it are standing still.

Galileo countered that the earth, the tower, and a rock held at the top of the tower are all moving forward with uniform velocity. When the rock is dropped, it gains downward velocity, but it doesn't give up its forward velocity. The downward and forward velocities are independent. Since the earth, tower, and rock have the same forward velocity, Galileo argued, the rock will not be left behind by the earth and tower. The rock will land at the foot of the tower. Furthermore, he explained, since the colleagues share the forward motion of the earth, tower, and rock, they are not in a position to observe the effects of the earth's movement.

To further explain his view to his colleagues, Galileo drew upon an analogy. He asked his colleagues to imagine a rock being dropped from the top of a ship's mast. Galileo said that, regardless of whether the ship is standing still or moving forward with constant speed in still water, the rock always lands at the foot of the mast. (The tower in the first scenario corresponds, of course, to the ship's mast.) The analogy is powerful because it introduces a new feature: a ship that can be either standing still or moving. The mast, unlike the tower, is connected to the ship, a body that the colleagues can view either in motion or standing still. In either event, the dropped rock lands at the foot of the mast. By means of this powerful analogy, Galileo successfully countered the argument of his colleagues and advanced his views concerning the rotation of the earth and moving frames of reference.

Analogy in Instruction Today

Just as they did in Galileo's time, scientists still make frequent use of analogies. In fact, analogies have played an important role in explanation, insight, and discovery throughout the history of science (Hesse, 1966; Hoffman, 1980). It is not surprising, therefore, that science teachers and textbook authors routinely use analogies to explain complicated concepts to students. Often, teachers and authors are unaware that they are using analogies — they do it automatically. Throughout their lessons, especially when responding to students' questions, teachers regularly preface their explanations with colloquial expressions such as "It's just like ... ," "It's the same as ... ," "It's no different from ... ," and "Think of it as ...." In textbooks, authors use more formal expressions like "Similarly," "Likewise," "Along related lines," "In comparison to ... ," and "In contrast with ...." These expressions are all ways of saying "Let me give you an analogy."

Unfortunately, teachers' and authors' analogies often do more harm than good (Duit, 1991; Gilbert, 1989; Thagard, 1992; Treagust, Duit, Joslin, & Lindauer, 1989). That is because teachers and authors, lacking guidelines for using analogies, sometimes use them unsystematically, which often causes confusion and misconceptions in their students. The distinctions among a target concept, features of the concept, examples of the concept, and an analogy become blurred in students' minds. One solution, of course, would be to advise teachers and authors not to use analogy. That would be unrealistic because teachers and authors, like all human beings, are predisposed to think analogically, and, they will use analogies, consciously or unconsciously, during explanation. The better solution is to introduce teachers and authors to a strategy for using analogies systematically to explain fundamental concepts in ways that are meaningful to students.

Purpose of Study

This National Reading Research Center report describes the role of analogy in instruction and presents new research on a model for teaching with analogies (Glynn, 1991, 1993; Glynn & Hynd, 1994). Task analyses of textbooks and exemplary teachers have been conducted to develop this model. The purpose of this model is to provide teachers and textbook authors with guidelines for constructing analogies and using them strategically during science instruction. The task analyses examine how exemplary teachers and authors construct effective analogies that help students activate, transfer, and apply relevant existing knowledge when learning from textbooks.

LEARNING SCIENCE MEANINGFULLY

Constructing Relations

Meaningful learning is the process of integrating new knowledge with existing knowledge. This process is complex and results from the interaction of key cognitive processes, such as forming images, organizing, and drawing analogies (Anderson & Thompson, 1989). The interaction of these processes leads to the construction of conceptual relations.

Science students should not be viewed as human video cameras, passively and automatically recording the information transmitted by teachers and textbooks. On the contrary, science students are active consumers of information — "informavores," if you will — who, when learning meaningfully, will challenge the information presented to them, struggle with it, and try to make sense of it by integrating it with what they already know.

One of the questions most often asked by both new and seasoned science teachers is "How can I help my students learn concepts meaningfully?" The answer is to help students learn concepts *relationally*, not by rote (Glynn, Yeany, & Britton, 1991). That is, students should learn concepts as organized networks of related information, not as lists of facts. Science teachers often realize this, but are not sure how to facilitate relational learning in their students, particularly when the number of students in a class is large and the concepts are complex. Complex, related concepts are the rule rather than the exception in biology (e.g., photosynthesis and mitosis-meiosis), chemistry (e.g., chemical equilibrium and the periodic table), physics (e.g., gravitational potential energy and electromagnetic induction), earth science (e.g., plate tectonics and precipitation), and space science (e.g., the sun and planetary motion). In one form or another, many of these concepts are introduced to children in the elementary school years; by high school, all students are expected to be scientifically literate, that is, to understand these complex concepts. So, teachers at all levels play a critical role in ensuring that students have a meaningful (relational) understanding of fundamental science concepts. To be successful in this role, teachers need powerful instructional strategies.

Strategies for Learning Conceptual Relations

Studies of experts and novices in fields such as physics (Chi, Feltovich, & Glaser, 1981) and biology (Feltovich, 1981) have shown that experts are experts, not just because they know more facts than novices, but because their knowledge exists in the form of interrelated networks. The relations in and among conceptual networks are of many kinds, including hierarchical, exemplifying, attributive, causal, correlational, temporal, additive, and adversative. In an expert, these relations contribute to a high-performance human "information-processing system." This system includes a working-memory component, analogous to a small cognitive workbench on which only a few cognitive operations can be performed at a time, and a long-term memory component, analogous to a set of file cabinets or a computer hard disk. Long-term memory provides raw material (knowledge) for working-memory operations and stores the products of those operations. The construction of conceptual relations enhances an expert's working-memory and long-term memory performance. Because the expert's knowledge is relational, it is easily stored, quickly retrieved, and successfully applied. Unfortunately, a student's knowledge is all-too-often rote, and is hard to apply, difficult to store, and often forgotten.

Teachers and textbook authors need powerful instructional strategies to help develop a student's information-processing system into that of an expert. *Concept mapping* (Novak, 1990) and *teaching with analogies* (Glynn, 1991) are two such strategies. Concept mapping does facilitate the learning of relations within a conceptual network. But what about relationships among different, but in some ways similar, conceptual networks? How can teachers and authors develop such relationships and use them to bridge conceptual networks? Teaching with analogies can provide answers to these questions.

Need for a Model

The role of analogical thinking in teaching and learning science has received increasing attention in recent years (Brown, 1993; Clement, 1989, 1993; Gentner, 1989; Lawson, 1993). Research findings suggest that teachers and textbook authors often use analogies, but use them ineffectively (Duit, 1991; Duit & Glynn, 1992; Glynn, Britton, Semrud-Clikeman, & Muth, 1989; Halpern, 1987; Halpern, Hansen, & Riefer, 1990; Thagard, 1992; Thiele & Treagust, 1991; Vosniadou & Schommer, 1988). Sometimes the analogies that teachers and textbook authors use to explain new concepts are clear and well developed, while at other times they are vague and confusing. Teachers and textbook authors need a model to guide their construction of instructional analogies systematically. Analogies could then be custom-tailored to suit students' own background knowledge. In response to this need, research on a model for teaching with analogies was initiated (Glynn, 1991, 1989a,b; Glynn et al., 1989; Harrison & Treagust, 1993; Thiele & Treagust, 1991).

Definition of Analogy

An analogy is drawn by identifying similarities between two concepts. In this way, ideas can be transferred from a familiar concept to an unfamiliar one. 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 common or similar features, an analogy can be drawn between them. An abstract representation of an analogy, with its constituent parts, appears in Figure 1. As can be seen in Figure 1, the analog and target are often examples of a *superordinate* (higher-order or cross-domain) concept.

An example of an analogy can be found in the high school textbook *Physical Science* (1988) in which the familiar concept *bookcase*

SUPERORDINATE CONCEPT

↙		↘
ANALOG	compared with ⟷	**TARGET**
↓		↓
Features 1,2,3, etc.	⟷	*Features 1,2,3, etc.*

⇕ ⇕ ⇕

TIERED SHELVING SYSTEM
(Superordinate Concept)

↙		↘
BOOKCASE (Analog)	*compared with* ⟷	**BOHR'S ATOM** (Target)
↓		↓
Books (*Feature*)	⟷	Electrons (*Feature*)
Number of Books per Shelf	⟷	Number of Electrons per Level
Shelves	⟷	Energy Levels
Number of Shelves	⟷	Number of Levels
Distances Between Shelves	⟷	Distances Between Levels
Floor	⟷	Nucleus

Figure 1. *Upper box.* An abstract representation of an analogy showing the relation of the superordinate concept to the analog and target and relation of the analog and target to the features. *Lower box.* An analogy between a bookcase and Bohr's atom that follows the abstract representation shown in the upper box.

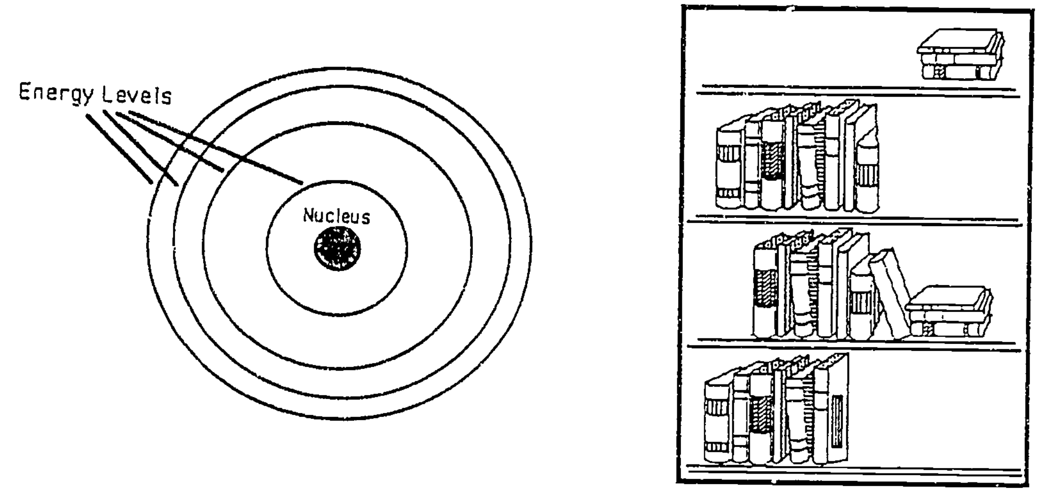

Figure 2. In Bohr's model of the atom, electrons are located in energy levels like shelves in a bookcase.

is the analog and the concept *Bohr's model of the atom* is the target. In the context of Rutherford's earlier model and Schrödinger's later one, Bohr's model is explained in the following way:

> According to the Bohr model, the electrons in an atom are not whirling around the nucleus in a random way. Instead, electrons move in paths. Each path is a certain distance from the nucleus. Compare Bohr's model to a bookcase.... Just as each shelf is a certain distance from the floor, each path is a certain distance from the nucleus. Also, the distance between one path and the next is not the same for each path, just as the shelves in some bookcases are not the same distance from each other. The paths in which electrons circle the nucleus are called energy levels. Electrons are found in energy levels, not between them, just as books are found on bookcase shelves, not floating between shelves. (Alexander et al., 1988, p. 85)

An analogy can be drawn between the bookcase and the atom because they share the similar features mapped in Figure 1. While a word mapping of features is sometimes sufficient for an analogy to be drawn, additional graphic or pictorial mappings are desirable because they activate the cognitive process of forming mental images, which helps students form better representations of the analogy. Figure 2 depicts the analogy in visual form.

The analog (bookcase) and the target (Bohr's atom) are examples of a superordinate concept we call a *tiered holding system*. Often, it is hard to identify and label the superordinate concept in an analogy that spans different conceptual domains. In such cases, teachers and textbook authors should try to create a verbal label, even when it sounds a bit peculiar.

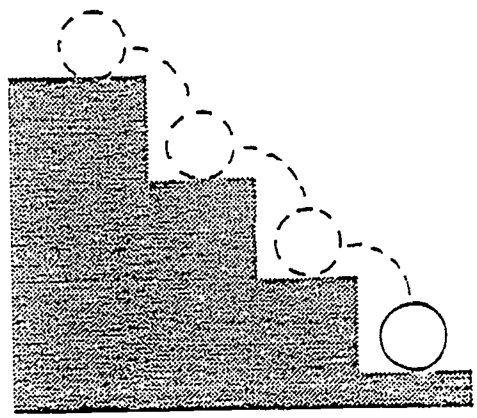

Figure 3. A stair-step representation of possible electron transitions.

It is worth the trouble to identify and name the cross-domain superordinate concept because that concept can suggest subordinate concepts that can also be used as analogs. For example. concepts subordinate to *tiered holding system* include *ladder* and *staircase*. Depending upon the purposes of the teacher or author, these could be better analogs than a bookcase.

No analog matches the target perfectly. Every analog breaks down at some point and no two analogs are alike. Each analog has its corresponding and noncorresponding features, and some will be better for some purposes than others. For these reasons, teachers and authors should try to suggest several analogs to students. For example, if the purpose is to demonstrate, by analogy, how an atom emits and absorbs light, a staircase analog can be more useful than a bookcase.

In their article, "The Stair-Step Atom," Jordan, Watson. and Scott (1992) describe how they use a specially constructed set of stair steps when teaching university general-studies astronomy and physics classes. The set of stair steps is an analog for a generic atom; the instructor — taking the role of an electron — jumps from a lower step to a higher one or vice versa (see Figure 3). The authors explain:

> Each step represents a possible energy level that an electron can have in our atom. The lowest energy level is on the floor and represents the ground state. The highest energy level is located at the top step. The region between the steps represents the differences in the energies of the two levels. This region is painted with a color that represents the wavelength of the energy — the photon — emitted by the atom as an electron changes orbits or steps. On the front is the color of the transition to the next step (state). On the side are colors that represent wave-lengths of photons emitted by the atom as electrons change their orbits (step) to the ground state, as well as to other energy levels. (p. 42)
>
> Our stair-steps model, like an atom, has discrete energy values.... The person playing the role of the electron must be one step (energy level) or another, not between steps. Our generic atom, in other words, is quantized. This simple analogy gives students a better understanding of what is going on inside an atom. (p. 44)
>
> An instructor plays the role of an electron in an atom that is undergoing the process of de-excitation. When he jumps from the top step to the middle step, he will emit a photon (throw a ping-pong ball) with

> the energy and wave-length (color) equivalent to the difference between the two steps. (p. 44)

Jordan et al. conclude by cautioning readers that their stair-step analog is simple and far from a true representation of an atom. At the same time, they believe the analog serves its purpose well in demonstrating how energy is released during de-excitation in an atom.

In summary, when students are provided several analogs such as the bookcase and staircase analogs of the Bohr atom, they can focus on the target concept from several perspectives and thereby come to a more complete understanding of it. Furthermore, when students are thinking in terms of several analogs, they are less likely to equate any one analog with the target. The additional analogs need not be developed in the same detail as the primary analog. A sentence or two emphasizing their unique features will often be sufficient.

The identification and labeling of a superordinate concept can prompt students to generalize and transfer what they have learned to other related concepts, not just features. That allows us to expand the earlier definition of an analogy: an analogy is a process of identifying similarities among two or more concepts. In other words, an analogy may involve an entire family of concepts, with concepts varying in the degree of family resemblance they share among themselves.

Analogical Transfer: Bridging Concepts

An effective analogy puts new ideas into terms already familiar to students. An analogy drawn by a teacher or author between a concept covered earlier in a course and one covered later is particularly effective because there is some assurance that the earlier concept is familiar to every student. For example, in *Conceptual Physics*, Hewitt (1987) explains the concept *gravitational potential energy* in Chapter 8 and uses it again in Chapter 33 to introduce students to the concept *electrical potential energy*:

> Recall from Chapter 8 the relation between work and potential energy. Work is done when a force moves something in the direction of the force. An object has potential energy by virtue of its location, say in a force field. For example, if you lift an object, you apply a force equal to its weight. When you raise it through some distance, you are doing work on the object. You are also increasing its gravitational potential energy. The greater the distance it is raised, the greater is the increase in its gravitational potential energy. Doing work increases its gravitational potential energy.
>
> In a similar way, a charged object can have potential energy by virtue of its location in an electric field. Just as work is required to lift an object against the gravitational field of the earth, work is required to push a charged particle against the electric field of a charged body. (It may be more difficult to visualize, but the physics of both the gravitational case and the electrical case is the same.) The electric potential energy of a charged particle is increased when work is done to push it against the electric field of something else that is charged. (pp. 501-502)

Ideally, an analogy effectively drawn between two concepts will help students transfer their existing knowledge to the understanding, organizing, and visualizing of new knowledge. The result is often a higher-order, relational understanding; that is, the students see how the features of a concept fit together and how the concept in question connects to other concepts. Thus, students will be more likely to generalize their understanding to a superordinate concept, such as that of potential energy. They also will be more likely to transfer their understanding to other instances of the superordinate concept, such as elastic potential energy and chemical potential energy, and see the similarities among different examples of potential energy, such as a lifted stone, a charged battery, a drawn arrow, and an unstruck match.

Effectiveness of an Analogy: Shared Features

The effectiveness of an analogy generally increases as the number of similar features shared by the analog and target increases. For example, teachers and textbook authors have traditionally used the camera as an analog when teaching about the human eye, because the two concepts have so many similar features. Consider the following excerpts from Hewitt's (1987) *Conceptual Physics*:

> In many respects the human eye is similar to the camera. The amount of light that enters is regulated by the **iris**, the colored part of the eye which surrounds the opening called the **pupil**. Light enters through the transparent covering called the **cornea**, passes through the pupil and lens, and is focused on a layer of tissue at the back of the eye — the **retina** — that is more sensitive to light than any artificial detector made.... In both the camera and the eye, the image is upside down, and this is compensated for in both cases. You simply turn the camera film around to look at it. Your brain has learned to turn around images it receives from your retina!
>
> A principal difference between a camera and the human eye has to do with focusing. In a camera, focusing is accomplished by altering the distance between the lens and the film. In the human eye, most of the focusing is done by the cornea, the transparent membrane at the outside of the eye. Adjustments in focusing of the image on the retina are made by changing the thickness and shape of the lens to regulate its focal length. This is called *accommodation* and is brought about by the action of the *ciliary muscle*, which surrounds the lens. (pp. 450-451)

The analogy between the camera and the eye is a powerful one because the analog and the target share many features. The camera is an effective analog, however, only when students are familiar with its features. Hewitt (1987) ensured his students' familiarity with the features of the camera by explaining its components in a section titled "Some Common Optical Instruments" that preceded the section on the eye.

Another powerful analogy, one with many corresponding features, is that between a mechanical pump and the human heart. Many authors and teachers assume that the students are familiar with the features of a pump. This assumption is often unjustified. Students might well be familiar with the pump-to-heart analogy, but that doesn't mean they have a clear understanding of how a pump works. Regardless of an analog's many shared features and time-honored connection with a target concept, authors and teachers should always take the time to ensure that students are familiar with the features of the analog before they attempt to draw an analogy.

It is possible to draw a good analogy on the basis of a few similar features, or even one feature, if it is directly relevant to the goals of the teacher or author. For example, consider the following analogy from Smallwood and Green's (1968) chapter on "The Molecules of Life" in their high school textbook, *Biology*:

> Most carbohydrate molecules can be compared to a freight train that is made up of boxcars linked together. Carbohydrate molecules are usually long chains of simple sugars bonded together. We call these large carbohydrate molecules **polysaccharides**. (p. 54)

The preceding analogy is simple; the train and boxcars correspond to the carbohydrate molecule and the sugars, respectively. Despite its simplicity, the analogy is effective because it maps a familiar mental picture (a freight train) onto the target concept (a carbohydrate molecule). The analogy helps the students to visualize quickly the general structure of the molecule.

The instructional value of an analogy decreases if it is difficult to identify and map the important features shared by the analog and the target. For example, consider this explanation of gravity and "black holes" in a physical science textbook:

> To understand black holes, astronomers study what happens when gravity is very strong. An object with a huge mass has such strong gravity that it bends space around it. The curved space bends any light that passes by. (Pasachoff, Pasachoff, & Cooney, 1983, p. 466)

The teacher's edition to this textbook provides teachers with the following question and analogy, presumably to aid them in their explanation of the effects of gravity:

> Is space curved or does gravity "pull on" the light? Analogy: two men walk side by side, ten feet apart, each perpendicular to the equator. To their surprise, they collide upon reaching the north pole. Question: Did gravity pull them together, or is the earth curved? (Pasachoff et al., 1983, p. 467)

The answer to the preceding question is clear: the earth is curved. But what is not clear is how the features of the analog — two men walking parallel to each other and perpendicular to the equator until they collide at the north pole — correspond to the target concept, the effect of gravity on space and light. In this analogy, there is a strong likelihood that misconceptions will be formed.

Misconceptions Caused by Analogy: The Dark Side

The advantage of teaching with analogy is that it capitalizes on students' relevant existing knowledge. Learning becomes relational rather than rote, and therefore it is more meaningful. The process of joining new knowledge to existing knowledge is intrinsically motivating. Analogical thinking is also efficient; it helps us to understand new phenomena and solve new problems by drawing upon our past experiences. This is the bright side of analogical thinking. There is a dark side as well. When students overgeneralize and map noncorresponding features of concepts, misconceptions can result (Thagard, 1992). This dark side of analogical thinking is an unfortunate fact of life.

On the first day of a science course, some high school teachers and college professors routinely advise their students: "Forget what you think you know about how the world works. You'll learn how it really works in this course." These professors and teachers have a poor understanding of how students learn meaningfully. Meaningful learning requires that students' existing knowledge be taken into account, not ignored. Conceptual bridges must be built between existing knowledge and new knowledge; analogy plays an important role in the construction of these bridges. Trying to avoid analogy is, to use another analogy, like throwing the baby out with the bath water. We seem to have a natural bent for analogical thinking. Even very young children reason analogically, as is illustrated by Jean Piaget's (1962) observation of his daughter Jacqueline when she was two years and 10 months old:

> J. had a temperature and wanted oranges. It was too early in the season for oranges to be in the shops and we tried to explain to her that they were not yet ripe. "They are still green. We can't eat them. They haven't yet got their lovely yellow color." J. seemed to accept this, but a moment later, as she was drinking her camomile tea, she said, *Camomile isn't green, it's yellow already.... Give me some oranges.* (p. 231)

Effective teachers and textbook authors capitalize on analogical thinking rather than ignore it. They make systematic use of analogy and emphasize to students that analogical thinking is powerful, but limited, and that wrong ideas can arise when an analogy is carried too far. For example, in their textbook *Concepts in Physics,* Miller, Dillon, and Smith (1980) explain to students:

> Models and analogies can be of great value in physics if they are used with care and discrimination. It is important, for example, to guard against the danger of believing that a model or analogy is an exact representation of some physical system. One should always regard a model critically and remember that an analogy means no more than: under certain special conditions, the physical system being studied behaves as if.... (p. 253)

Analogies are double-edged swords. An analog can be used to explain and even predict some aspects of the target concept; however, at some point, every analogy breaks down and, at that point, misconceptions may begin. Since two concepts are never completely identical, differences always exist among their defining features. For example, consider an analogy used to explain drug overdose from a chapter on "Drugs and Behavior" in the high school textbook *Biology: An Everyday Experience* (Kaskel, Hummer, & Daniel, 1988). One of the accompanying figures is of a partially stoppered sink, with water flowing into the sink and out of it at the same rate. Another figure shows an overflowing sink, with more water flowing into it than can drain out. The explanation in the text reads:

> The body balances the amount of drug entering and leaving it. Think of the water going into the sink as a drug ent :ring the body. The leaking stopper stands for the organ removing the drug. If the water entering the sink is equal to the water leaving it, the water will not overflow. Nor will the sink become empty. The same type of thing happens with a correct drug dose. With the proper drug dose, the amount of drug entering the body equals the amount leaving it.
>
> What happens if a person does not take the correct drug dose? A drug overdose could result. An **overdose** is the result of too much of a drug in the body. Let's look at the sink example again. [The figure] shows what might lead to a drug overdose. Too much of a drug is added to the body. The body cannot get rid of the drug fast enough, and a drug overdose results. (p. 332)

The preceding analogy, drawn between water in a sink and a drug in the body, could easily lead to a misconception. While the authors note, "Drugs taken into the body soon leave it or change into a different form," the analog nevertheless promotes the misconception that a prescription or nonprescription drug flows through the body without interacting physically and chemically with its constituents. Unless cautioned otherwise by the authors or teachers, students could assume that a drug such as alcohol poses few risks if it flows through them and soon exits in urine.

A careful examination of all features of an analogy is a prerequisite to using it effectively in instruction. When teachers and authors use an analogy, they should anticipate analogy-caused misconceptions and eliminate them by pointing out to students where the analogy breaks down.

TEACHING-WITH-ANALOGIES MODEL: RESEARCH AND DEVELOPMENT

Research on a model for teaching with analogies began with a task analysis of middle school, high school, and college science textbooks; the analysis identified how the authors of 43 textbooks used analogies to explain new concepts to students. The task analysis of textbooks has now been supplemented by an analysis of the lessons of exemplary science teachers.

Task Analysis: A Research Method

Task analysis was used in the present research "with the intent of modelling an individual expert's thinking" (Wiggs & Perez, 1988, p. 267). Task analysis (Gagne, 1985; Gardner, 1985), also called a procedural analysis, is a technique that "identifies and structures the basic processes that underlie task performance.... You are trying to document the basic processes that are involved in performing a cognitive task" (Goetz, Alexander, & Ash, 1992, p. 360). A task analysis of how experts perform a cognitive task leads to a representation of the experts' knowledge and, eventually,

Table 1. Operations in the Teaching-with-Analogies Model:

1. Introduce target concept.
2. Cue retrieval of analog concept.
3. Identify relevant features of target and analog.
4. Map similarities between target and analog.
5. Indicate where analogy breaks down.
6. Draw conclusions.

to a model of the task that includes the operations carried out in the performance of the task. For example, a task analysis of expert writers led Flower and Hayes (1981) to a model of competent expository writing; the model has subsequently played an important role in the instruction of novice writers (Hayes & Flower, 1986). Likewise, in the present research, task analyses of science textbooks and exemplary teachers were expected to lead to a model for teaching with analogies — a model that could provide less experienced authors and teachers with guidelines on how to use analogies effectively.

Research Findings: Textbooks

A task analysis was conducted on the analogies in 43 middle school, high school, and college textbooks (see Glynn, 1991; Glynn et al., 1989). The sentences comprising the analogies in each textbook were examined. For each sentence or group of related sentences (called *statements*) the question was asked: "What is the author's intention here?" This question, alternatively stated, is: "What operation is the author performing?" The statements were sorted into categories. A summary of these data for all textbooks indicated that the statements fell into six main categories, each corresponding to an operation. The operations that underlie these categories are shown in Table 1. Together, these six operations form the basis of the Teaching-with-Analogies Model. The order of the six operations listed in Table 1 is only approximate. The authors actually varied with respect to the order in which they carried out operations, the number of operations they carried out, and the number of times they carried out any given operation.

While all of the textbook authors were considered to be experts, the analysis identified the analogies drawn by Hewitt (1987), author of *Conceptual Physics*, as being among the best. He consistently uses the six operations listed in Table 1, and draws analogies, not only between concepts, but between principles and formulas as well. For example, in *Conceptual Physics*, he draws a detailed analogy between Newton's law of gravitation and Coulomb's law of electrical force. A graphic map of this analogy appears in Figure 4.

In his text, Hewitt introduces the target concept, Coulomb's law, by reminding students of the analog concept, Newton's law, which he had explained in an earlier chapter:

> Recall from Newton's law of gravitation that the gravitational force between two objects of mass m_1 and mass m_2 is proportional to the product of the masses and inversely proportional to the square of the distance d between them: $F = G(m_1m_2/d^2)$, where G is the universal gravitational constant. (pp. 482–483)

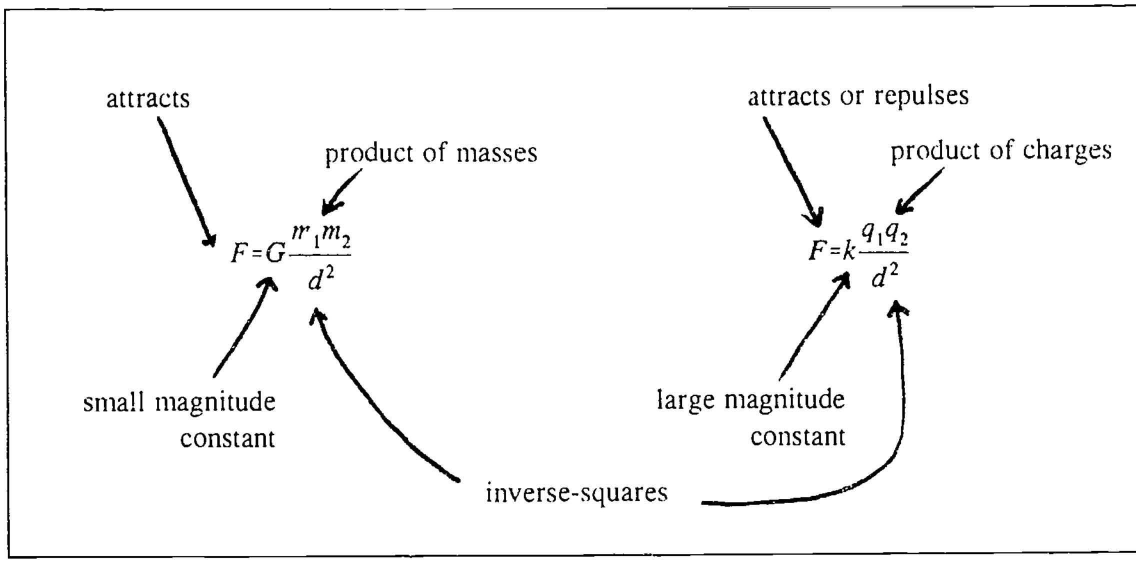

Figure 4. A comparison of two inverse-square laws: Newton's law of gravitation and Coulomb's law of electrical force.

Hewitt does not just remind students of the analog, Newton's law; he briefly re-teaches it, identifying the key features and relations in the analog. Hewitt knows that some students will forget Newton's law, entirely or in part, and they will not take the time to flip back to the earlier chapter. So, he refreshes their memory for them. Next, Hewitt identifies the features and relations of the target concept, Coulomb's law:

> The electrical force between any two objects obeys a similar inverse-square relationship with distance.... Coulomb's law states that for charged particles or objects that are small compared to the distance between them, the force between the charges varies directly as the product of the charges and inversely as the square of the distance between them. The role that charge plays in electrical phenomena is much like the role that mass plays in gravitational phenomena. Coulomb's law can be expressed as: $F = k(q_1q_2/d^2)$ where d is the distance between the charged particles; q_1 represents the quantity of charge of one particle and q_2 the quantity of charge of the other particle; and k is the proportionality constant. (p. 483)

Then, Hewitt maps the similar features and relations of the concepts. He is careful to point out where the analogy breaks down. By doing so, he reduces the likelihood that students will overgeneralize from the analog to the target concept and form misconceptions:

> The proportionality constant k in Coulomb's law is similar to G in Newton's law of gravitation. Instead of being a very small number like G, the electrical proportion-

ality constant k is a very large number.... So Newton's law of gravitation for masses is similar to Coulomb's law for electric charges. Whereas the gravitational force of attraction between a pair of one-kilogram masses is extremely small, the electrical force between a pair of one-coulomb charges is extremely large. The greatest difference between gravitation and electrical forces is that while gravity only attracts, electrical forces may either attract or repel. (pp. 483–484)

Finally, Hewitt draws main conclusions for students about both the target concept (electrical force) and the analog (gravitational force):

> Because most objects have equal numbers of electrons and protons, electrical forces usually balance out. Any electrical forces between the earth and the moon, for example, are balanced. In this way the much weaker gravitational force, which attracts only, is the predominant force between astronomical bodies.
>
> Although electrical forces balance out for astronomical and everyday objects, at the atomic level this is not always true. The negative electrons of one atom may at times be closer to the positive protons of a neighboring atom than to the electrons of the neighbor. Then the attractive force between these charges is greater than the repulsive force. When the net attraction is sufficiently strong, atoms combine to form molecules. The chemical bonding forces that hold atoms together to form molecules are electrical forces acting in small regions where the balances of attractive and repelling forces are not perfect. (pp. 484–485)

To illustrate the implications of his conclusions, Hewitt provides students with a concrete example in which he compares the electrical and gravitational forces between the proton and the electron in a hydrogen atom. By means of this example, he shows students that the electrical force in the hydrogen atom is much greater than the gravitational force. So much so, that the gravitational force is negligible. Hewitt also points out to his students that the similarity between the law of gravitational force and the law of electrical force may point the way to new discoveries in science:

> The similarities between these two forces have made some physicists think they may be different aspects of the same thing. Albert Einstein was one of these people; he spent the later part of his life searching with little success for a "unified field theory." In recent years, the electrical force has been unified with the "weak force," which plays a role in radioactive decay. Physicists are still looking for a way to unify electrical and gravitational forces. (p. 484)

Hewitt's use of analogies is exemplary, but many authors use analogies ineffectively. The task analysis of 43 science textbooks revealed some instances in which authors suggested a sketchy analogy to students, and then abandoned the analogy, leaving students to make sense (or nonsense) out of it for themselves. Under these conditions, students could identify irrelevant features of the target and analog concepts, map these features, fail to realize where the analogy breaks down, and draw wrong conclusions about the target and analog. In other words, the misguided use of analogies by some authors could actually promote misconceptions in students.

Research Findings: Teachers

The task analysis of textbook analogies was supplemented by a task analysis of the lessons of 10 exemplary science teachers (see Glynn, 1993; Glynn, Law, & Gibson, 1994). The exemplary science teachers were from public middle schools. The teachers were identified as exemplary by means of awards and the judgments of principals, other teachers, and university teacher educators. All classes were multicultural, with 18 to 25 students in each class. The lessons were observed and videotaped; a task analysis of the lessons was conducted. The teachers later re-enacted their lessons in a video studio and were asked to explain the decisions they made during the course of their lessons.

Each teacher selected a lesson in which he or she made the best possible use of analogy-based activities to elaborate on a key concept that the students had read about in their textbooks. For example, one of the teachers, Martha Gilree, taught an earth science lesson on the structure of the earth. She baked layered cupcakes for her students and explained that the cupcakes were analogs of the earth, with the four layers corresponding to the crust, mantle, outer core, and inner core of the earth. Using straws, the students took "core samples" from the cupcakes, examined the samples, and compared them to representations of the earth in their textbooks.

Another teacher, Joe Conti, taught a biology lesson on natural selection and the concept of survival of the fittest. He took his students outside to an area of green grass where earlier he had scattered an equal number of green, brown, and red uncooked noodles. He explained that the noodles were analogs for different colored grasshoppers and that the students were hungry birds who preyed on the grasshoppers. The students "caught as many grasshoppers" as they could in the next five minutes and returned to the classroom where a tally revealed that fewer green grasshoppers were caught than brown, and fewer brown than red. Joe then explained to his students how a trait such as coloration can increase or decrease the probability a species will survive in a given environment.

Still another teacher, Becky Wheeler, taught a physical science lesson on optics. She and her students built a simple, working camera and she used this camera to explain optic principles (see Table 2). Becky then explained that the camera is an analog for the human eye and, using a physical model of the eye, she compared its features to those of the camera. Finally, she taught optic principles common to the camera and eye.

A task analysis was carried out on the videotaped statements and actions that made up the lessons of the 10 exemplary teachers. In each lesson, a statement was one sentence or a few related sentences on either a target concept (e.g., the eye), an analog concept (e.g., the camera), or a conceptual feature (e.g., the lens). For each statement, the question was

Table 2. Becky Wheeler's Lesson on Optics

Statements	Operations
One of the things we're going to learn today is what the eye looks like.	1
If I were to take out my eye, anyone else's eye and put it on a plate, they'd look pretty much the same; they'd be about the same size. [Teacher shows ping-pong ball.]	2/3
What do you call the eye, generally? How would you refer to the eye if you took it out like this? Yes, an eyeball.	2
We call it a ball because it's round and actually this ping-pong ball is about the same size as an eye.	3/4
How many of you think you know what this is? [Teacher shows a glass lens.]	2
Actually, if you wanted to know what the eye looks like, the lens of it looks like this.	3
Now, it's not exactly the same material because the eye is made of soft tissue and this is made of glass. It looks a lot like this but it's not this big; this is much bigger.	5
Okay, let's look at a model of our eye. [Teacher shows plastic model of eye.]	2
We can see this white part, which is sort of a tough tissue and it's called the sclera.	3
You can see this bulging part...put your finger on your eye and move it right and to the left. Can you feel the bulge? Who knows what that bulge is called? Yes, the cornea.	3
The part that goes around the pupil and changes the size of the hole is the iris—that controls the amount of light and changes the size of the pupil.	3
Actually, it can get as tiny as the end of a pencil and as large as about the size of the eraser on the other end. [Teacher shows and compares pencil features.]	2/4

The clear transparent part on the front is called the aqueous humor.	3
Inside your eye is a gel-like solution called the vitreous humor and it helps to give the eye its shape.	3
The light has to come in; it goes through the pupil...and finally it gets to the back of the eye. What is that called? Okay, the retina.	3
A lot of times we compare the eye to a camera.	2
Think about the parts we just talked about...an eyelid...what could we compare the eyelid to on this camera? Yes, the shutter. [Teacher shows and compares camera.]	4/6
On the camera, what do you have that controls the light that goes into it, comparable to the iris that controls the amount of light going into the eye? Yes, the aperture.	4/6
The lens, we said, is an important part of the eye; and of course, the camera has a lens.	4
You told me that you have a retina on the back of your eye that's light-sensitive. What do you have on the back of the camera that's light-sensitive? Okay, light-sensitive paper — the film.	4/6
On our retinas we have special nerve cells that can pick up black and white color. These are called rods, and we have some cells called cones that pick up colors. So on a camera, what do you think we could use to compare to the rods?	4/6
Now the optic nerve in our eye takes the message to the brain; you know the camera doesn't have that.	5
Okay, the vitreous humor — that's part of the eye, but it's not a part of the camera.	5
Does anyone know what I have here? A pinhole camera. [Teacher shows homemade, tube-like pinhole camera.]	2
What do you think this part, the shutter, would be compared to? Yes, the eyelid.	4/6
Then we've got the little pinhole, the aperture; what could we compare that to? The pupil, the iris working together.	4/6

On the very back, we have the light-sensitive paper; what part of the eye would you compare that to? Yes, the retina.	4/6
Okay, there's a wonderful part of your eye that controls the lens — so that the lens in your eye is different from the lens in a camera. In the lens in a camera you have to have a way of adjusting it to make it focus, but the lens in our eye has special muscles called ciliary muscles. They can make the lens flat and they can make the lens thin.	5
Okay, the retina on the back of the eye is different from the film of the camera because it's very small...	5
...it's actually about the size of a postage stamp.	2/4
All of the nerve fibers come together and form something like a cable; that is where the optic nerve attaches.	2/4
[Teacher shows poster of traffic signal and eye; string represents light rays.] All of the light rays are coming from this red light...when it comes it's straight and when it gets to this area, it is going to bend so that it ends up here on the back of the eye.	2
Now, what has happened to the image? Yes, it's turned upside-down.	6
[Teacher shows a glass lens.] This is just like the lens in your eye: light travels in a straight line, comes through the lens...	2
Look at me through this lens; how do I appear to you? [Students look and see upside-down image of teacher.]	6

Note. See Table 1 for Operations 1 through 6.

asked: "What operation is the teacher performing?" The statements were sorted into categories, tallied, and summarized for all teachers. The teachers were found to use the six operations that the textbook authors did, as well as several others. For example, some identified concepts that are superordinate to the target and analog concepts, such as: The science of optics is superordinate to the concepts *eye* and *camera*. These other operations were relevant to the analogies, but were unessential and performed infrequently. None accounted for more than 2% of the statements. Because they were unessential and infrequent, these other operations were not added to those already in the Teaching-with-Analogies Model (see Table 1).

Thirty-five sample statements and the corresponding operations for the lesson on optics taught by Becky Wheeler are presented in Table 2. (The operation numbers in Table 2 correspond to those in Table 1.) Becky Wheeler, like the other teachers, carried out the operations in an order that roughly corresponds to the order in Table 1. Two independent raters viewing the videotapes agreed 86% of the time on the categorization of the transcribed statements; the raters resolved the other 14% through discussion. The teachers' statements, which were spontaneous and oral, were more difficult to categorize than the written statements of the authors. The content and grammar of the teachers' statements were less structured and precise than those of the authors. In addition, the teachers' statements frequently included questions that the students were asked to answer; after the students answered, the teacher then provided feedback. For example, Becky Wheeler mapped similarities (operation 4) between an eye and a camera and asked students to draw conclusions (operation 6): "Think about the parts we just talked about... an eyelid...what could we compare the eyelid to on this camera? [The students responded "Shutter!"] Yes, the shutter." As a result of this interactive questioning, two-operation statements were more common among teachers than authors.

As can be seen in Table 2, the primary analogy in Becky Wheeler's lesson on optics is drawn between a camera and the human eye; however, it is important to note that there are secondary analogies as well. These include comparing the eyeball to a ping-pong ball, the optic nerve fibers to a cable, and the eye itself to a plastic model and to a traffic light. The other teachers' lessons were similar in this respect: each included a primary analogy, but also made use of several related, secondary analogies.

DISCUSSION

The task analyses of textbook authors and exemplary teachers indicated that, in practice, the order in which the six Teaching-with-Analogies operations are carried out can vary. It is usually important, however, for the teacher or textbook author to perform all of the operations. If the teacher or textbook author were to perform only some of the operations, leaving some to the student, it is possible that the student might fail to perform an operation or might perform it poorly. The result could be that the student will misunderstand the concept being taught.

It is reasonable to assume that teachers and textbook authors will use the process of analogy more effectively if they keep the Teaching-with-Analogies Model in mind. They can mentally check off the six operations in the model when constructing an analogy to explain a new concept. When an author doesn't perform some of the operations in the model and the analogy suffers as a result, the teacher can perform them for the students. Or, when the author's analogy is effective and the teacher wants to extend it, the teacher can use the model for this purpose, thus increasing the instructional value of the analogy.

Recently, Harrison and Treagust (1993) carried out an extensive case study in which an experienced science teacher was trained with the Teaching-with-Analogies (TWA) Model and used it to teach a lesson on optics and the refraction of light. For purposes of teacher training, Harrison and Treagust modified the model by reversing the order of the final two operations (see Table 1). As noted previously, the order of the operations does vary in practice; however, it may be that one order is better than others for purposes of introducing the model to teachers. Regarding the effectiveness of the model, they concluded:

> Based on the data collected over four lessons ... it is asserted that in this instance, with this teacher, a systematic approach like the modified TWA model is a practical and achievable means for improving the use of analogies in science classrooms.... At the conclusion of three episodes during which Mrs. Kay used the modified TWA model, she appeared to be competent and fluent in its use and the students responded positively to the resultant analogical instruction. As shown by this data, there was a consistently high level of understanding encountered during the interviews. In the described lesson, Mrs. Kay felt that the students had understood refraction better than on any previous occasion that she had taught this concept. Based on our studies with this teacher and five other teachers, it is predicted that the majority of practicing teachers would require extended practice combined with critical feedback in order to integrate the modified TWA model into their pedagogical repertoire. (pp. 1293)

Teachers also are encouraged to use the Teaching-with-Analogies Model to construct additional analogies to complement an author's analogy. Several analogies constructed for the same concept can help the students view the target concept from different perspectives. The analogies function like conceptual lenses, with each one bringing different features of the concept into sharper focus. For example, several analogies can be used to discuss views of how galaxies are arranged in the universe:

> Astrophysicists closing in on the grand structure of matter and emptiness in the universe are ruling out the meatball theory, challenging the soap bubble theory and putting forward what may be the strongest theory of all: that the cosmos is organized like a sponge.
>
> This new concept holds that a surprisingly complex arrangement of clustered galaxies stretches in connected tubes and filaments from one end of the universe to the other and that galaxy-free voids form an equally complex, equally well-connected structure.
>
> Far more rapidly than was possible a few years ago, scientists are assembling data from the most distant galaxies to produce a picture of the universe's structure. The sponge idea is meant to resolve a clash between views of the universe as clumps of matter on an empty background (the meatball concept), or as empty voids carved out of a full background (the bubbles concept). ("Sponge Concept," 1986, p.7).

All three analogies — meatball, soap bubble, and sponge — are useful in explaining views of how galaxies are arranged. These views are similar but have important differences. Each analogy, with its particular constellation of features, has its own explanatory power.

FUTURE DIRECTIONS FOR RESEARCH: STUDENT-GENERATED ANALOGIES

The research described in this report has focused on how teachers and textbook authors can construct effective analogies to help students comprehend textbook concepts. Future research will also focus on determining how students can construct effective analogies for themselves, independently of teachers and textbook authors. Research and development will begin on a variation of the Teaching-with-Analogies Model, called the Learning-with-Analogies Model. It is anticipated that students who are taught how to use a Learning-with-Analogies Model will be able to interpret. criticize, and extend analogies provided by authors and teachers.

A lively class discussion in which an analogy is dissected by students who understand the Learning-with-Analogies Model could help students to better understand the target concept and, at the same time, help the teacher to diagnose misconceptions the students might have. For example, middle-school teachers sometimes compare the process of photosynthesis to baking a cake (Glynn, 1989b). This analogy helps teachers identify those students who mistakenly believe that plants get their food directly from the soil (i.e., use plant food) rather than make their own food from raw materials in the air and soil (i.e., water and carbon dioxide). Many students have seen someone baking a cake and are therefore familiar with the analog. By asking students to explain how baking a cake is like photosynthesis, teachers can identify students who have misconceptions about photosynthesis. Teachers can then use the analog to correct the misconception. This analogy, like all analogies, breaks down at various points, and teachers can use these points to further assess students' true understanding of the target, photosynthesis.

Students could also use a Learning-with-Analogies Model as a guide when constructing their own analogies. For example, students seeking an alternative to the baking-a-cake analog for photosynthesis might use a building-a-house analog to construct their own analogy: Raw materials (lumber + nails + shingles) + energy from a carpenter → final product (house) + waste products (sawdust + scrapwood). The final and waste products correspond to sugar and oxygen, respectively (see Kaskel, Hummer, & Daniel, 1988, pp. 360 - 362, for a detailed version of this analogy).

Even when authors and teachers have provided analogies for a particular concept, it is advantageous for students to construct their own analogies because students must then use their own relevant knowledge. This ensures that the analogies will be meaningful. In addition, students who can construct their own analogies become more independent in their learning. They can tackle new concepts on their own, using analogical reasoning as a way of understanding those concepts.

Author's Note. For information on how to obtain the NRRC Video Highlight, "Teaching Science with Analogy: Building on the Book," please write to the

National Reading Research Center, 318 Aderhold Hall, University of Georgia, Athens, GA 30602.

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