On the Role of Analogies and Metaphors in Learning Science

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INTRODUCTION

It has frequently been argued that analogies may be valuable tools in teaching and learning difficult scientific concepts (cf. Bauer & Richter, 1986; Gee, 1978; Göbel, 1976; Klinger, 1987; Webb, 1985; Weller, 1970), but there are also more skeptical positions. Kircher (1989), for instance, follows Bunge (1973, p. 127), who stated that analogy may give birth to as many monsters as healthy babies.

In the past 15 years much research (empirical as well as analytical) on analogy use has been carried out. The present paper tries to present an overview of this research. It includes metaphors in an analysis of the educational power of analogies. Analogies and metaphors are viewed as close relatives. It will be seen, amongst other things, that analogies may be valuable tools in conceptual change learning if their "metaphorical" aspects are regarded. The paper deliberately takes a constructivistic position. The role of analogies in the learning process is mainly analyzed from this perspective.

ON THE MEANING OF ANALOGY AND METAPHOR

Care is necessary when comparing what is said in literature about analogy and metaphor. Different authors usually have different—sometimes substantially different—concepts in mind when employing these terms. In the following, an attempt is made to outline the way the terms are used in the subsequent sections of this paper.

On the Meaning of Analogies

The use of the term analogy in this paper refers to comparisons of structures between two domains. Figure 1 outlines what is meant in a more formal way. All the boxes stand for representations (R). As portrayed in a pictorial way, there may be identical features in parts of the structures of R_1 and R_2. R_M represents this structural identity. We call R_M a model. There is an analogical relation between

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R_1 and R_2 as follows. R_1 and R_2 are *analogous with regard to the structure presented in R_M*. There may be analogical relations on different levels. If R_1 and R_2 are representations of two domains of reality (e.g., water and electric circuit), the analogy relation as portrayed in Figure 1 may be called an analogy of the first level. But analogical relations are also conceivable between two models.

There is another important feature of the analogical relation. It is symmetrical, because it is based on identities of parts of structures. The terms analog and target do not therefore indicate some sort of logical hierarchy. They are terms that indicate the purpose of analogy use. We refer to the domain that functions as a "base" (Gentner, 1983) or "source" (Rumelhart and Norman, 1981) in the process of learning or teaching as an *analog* (here we follow Glynn, 1991; Glynn et al., 1989). We call the domain that is explained or learned by harnessing the analogy a *target*. There is much more concurrence in literature concerning this term than the term analog. Gentner (1983), Glynn et al. (1989), and Rumelhart and Norman (1981) use it.

On the Meaning of Metaphors

> Taken as literal, a metaphorical statement appears to be perseverely asserting something to be what it is plainly not. . . . But such "absurdity" and "falsity" are of the essence: in their absence, we should have no metaphor but merely a literal utterance (Black, 1979, p. 21).

In fact, if one calls education "sheep herding" (Black, 1979, p. 25) or a teacher "the captain of the ship" (Fraser & Rennie, 1988), and takes these statements literally, they are absurd. A metaphor compares without doing so explicitly. It appears to be the very essence of a metaphor that the grounds of the comparison are hidden. Metaphors always have some aspect of surprise; they provoke anomaly. In this sense metaphors are comparisons where the basis of comparison must be revealed or even created by the addressee of the metaphor.

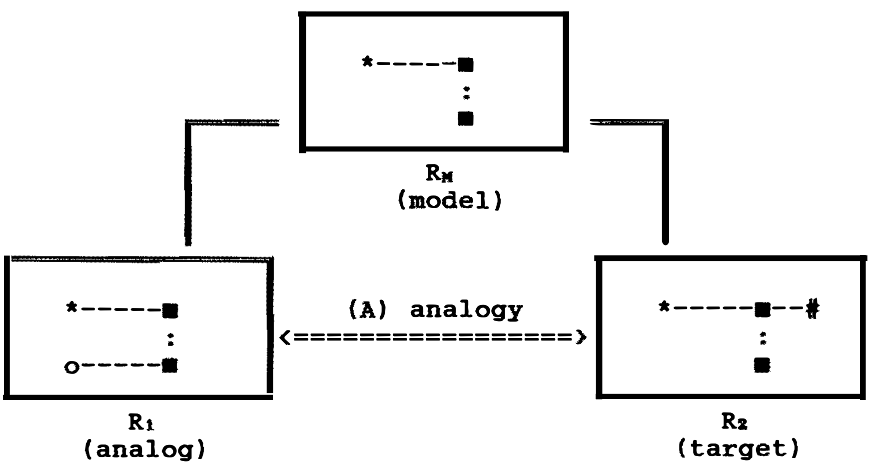

Figure 1. On the meaning of analogy

Analogies and Metaphors

Both analogies and metaphors express comparisons and highlight similarities, but they do this in different ways. An analogy *explicitly* compares the structures of two domains; it indicates identity of parts of structures. A metaphor compares *implicitly,* highlighting features or relational qualities that do not coincide in two domains. Taken literally, metaphors are plainly false. Viewed within the framework of Figure 1, one could say that a metaphor points out some major dissimilarities in order to incite the mind to search for similarities. Analogies and metaphors may therefore be viewed as polarities, which in principle may be transformed into one another; that is, analogies may be seen as metaphors, metaphors as analogies. As will be argued below in greater detail, the "metaphorical" view is of great importance where the role of analogies in the learning process is concerned.

Analogies and Models

The term model is used in many different senses (cf. Bunge, 1973, p. 91; Leatherdale, 1974, p. 41; Lind, 1980). Quite often not even single authors are very consistent in the way they use this term. But there appears to be some concurrence in that models, like analogies, have to do with the structural mapping of different domains. They usually represent parts of structures of target domains. Our use of the term model in Figure 1 may be seen as such. Models may, therefore, provide analogies. It is the analogy relation that makes a model a model. Unfortunately, it is quite common to use the term analogy not only for what has been called here the analogical relation but also for the analog domain (cf. Leatherdale, 1974, p. 2). It is, therefore, no surprise that model and analogy are frequently used interchangeably. The water model of the electric circuit is often called the water analogy. The same holds true for many other such models or analogies.

Analogies and Examples

Analogies and examples serve similar purposes in the learning process insofar as they are both used to make the unfamiliar familiar. At first sight, it appears to be possible clearly to differentiate between analogies and examples. "An example is an instance of a concept not a comparison between similar features of two concepts" as Glynn et al. (1989, p. 385) put it. But examples may be viewed as analogies or used in this way. If, for instance, a student associates further examples with a given concept, he or she clearly makes statements that involve comparisons. These are referred to as analogies here. The many examples usually given to portray the features of a concept, hence, may be viewed as standing in an analogical relation.

ON THE ROLE OF ANALOGIES AND METAPHORS IN THE LEARNING PROCESS

The role of analogies in the learning process has been analyzed from different theoretical perspectives (see the overview in Shapiro, 1985). It is beyond the scope of this paper to portray the relevant literature in detail. Only some aspects that coincide with the focus of the paper will be presented here.

Analogies and Learning

Rumelhart and Norman (1981) have outlined a schema theory perspective. Schemata in this perspective are packages of knowledge based on specialized procedures that are employed in the interpretation of events in our environment. They distinguish three kinds of learning. The first one is called *accretion,* i.e., the encoding of new information in terms of existing schemata. No new schemata are developed in this kind of learning. It appears to be very similar to Piaget's (1953) assimilation process. The generation of new schemata occurs only in the other kinds of learning namely *tuning or schema evolution* and *restructuring or schema creation.* Here analogies come into play. New schemata are generated by analogy, by transferring structures from source domains (i.e., what we refer to as analogs here) to target domains. These kinds of learning apparently share main features with Piaget's accommodation process.

There is another aspect of analogy use in the learning process discussed by Shapiro (1985) that is of importance: analogies may make new information more concrete and easier to imagine. This is also highlighted by several other authors (cf. Black, 1979; Davidson, 1976; Paivio, 1983). But it appears not to be totally clear in which way "analogical visuals" ease learning except that they relate the new to something very familiar to the learner.

The "constructivistic view" (cf. von Glasersfeld, 1983; Wittrock, 1985) has become the leading theoretical perspective of science education research on learning processes in the past ten years. The theoretical positions underlying the previous paragraphs (e.g., the schema theory perspective) coincide with main aspects of the constructivistic view. The following two basic ideas of this view are of central importance: (1) learning is an active construction process; and (2) learning is possible only on the basis of previously acquired knowledge. Accordingly, learning is not an intake of "nuggets of truth" [as one of the forerunners of contemporary constructivism, Kelly (1955), put it] but a process of actively employing the already familiar to understand the unfamiliar. Learning, therefore, fundamentally has to do with constructing similarities between the new and the already known. It is precisely this aspect that emphasizes the significance of analogies in a constructivistic learning approach.

More "traditional" views of learning (e.g., Gagne, 1970) also emphasize, of course, the necessity of relating the unfamiliar to the familiar. But learning appears to be viewed mainly as conceptual growth, i.e., as a continuous chain of enlargements. Accordingly, "definitions" (quite often they are only "verbal outlines") are employed to point out in which way the new concept or principle relates to the already known. Examples (Gagne emphasizes the importance of them) serve the same purpose. The constructivistic view of learning admits that much learning may be viewed in terms of conceptual growth, but what is principally different in this view is that learning is often not simply a continuous chain of enlargements but a totally new construction of the already known. Kuhn (1970) has called comparable processes in the history of science "paradigm shifts." In the field of constructivism, they are discussed under the heading of "conceptual change" (cf. West & Pines, 1985). Analogies are of pivotal importance in conceptual change learning in that they may help to restructure existing memory and to prepare it for new information (Gentner, 1983; Shapiro, 1985). The symmetrical nature of the analogical relation between analog and target mentioned above comes into play here. Employing an analogy does not merely help or facilitate learning in a new domain, it also opens up new perspectives for viewing and, hence, restructuring the analog. Using an analogy is, therefore, essentially a "two way" process involving developing both analog and target (cf. Bauer & Richter, 1986; Steiner, 1988).

Metaphors and Learning

It is the above-mentioned "surprise" or "anomaly" aspect of metaphors that makes them significant in the learning process. "Something happens to us when we first read a fresh metaphor. We are reorganizing our patterns of previously organized meaning" (Gowin, 1983, p. 38). Metaphors may open up new perspectives to us and may even help us to see the familiar in totally new ways. Gowin (1983) discusses, for instance, the metaphor "A paintbrush is a kind of pump." This, initially, is a surprising statement. It provokes thought, and hence, invites us to construct analogical relations that provide the statement with a sound meaning. This "generative power" of metaphors makes them potentially valuable tools in conceptual change learning. They provide what is essential to this aspect of learning, namely making it easier to restructure the already known and familiar (cf. Howard, 1989; Muscari, 1988; Sutton, 1978, 1981). The use of anomalies and cognitive conflict has been discussed extensively in educational psychology (cf. Berlyn, 1966; Festinger, 1962). Cognitive conflict also possesses significant value as part of conceptual change (cf. Driver & Erickson, 1983). Metaphors are one possible way of producing an anomaly and, hence, inciting a cognitive conflict.

There are other aspects of metaphors that are of importance for learning. Usually, they provide a degree of imagination, and help us to visualize abstract ideas (Davidson, 1976; Miller, 1979). They also appear to link thinking with feeling (Gowin, 1983). Hence, they may bridge the gap between the cognitive and affective domains of learning.

As has been outlined above, analogies differ from metaphors, but only to a slight degree. Hence, every good analogy contains some aspects of surprise and anomaly or at least may be used in this way. What has been outlined above about the role of metaphors in learning, therefore, holds true—at least partly—also for analogies. It is the metaphorical aspect of good analogies that makes them valuable tools in conceptual change learning.

EMPIRICAL RESEARCH ON THE ROLE OF ANALOGIES IN LEARNING

In the following sections, an attempt is made to summarize the results of empirical research on the role of analogies in the learning process that has been carried out in the fields of analogical reasoning and science education research.

Spontaneous Use of Analogies

The research on student's scientific conceptions (see the overviews in Pfundt & Duit, 1991; Duit, 1991) indicates that students frequently try to make sense of phenomena by employing analogies from areas that are familiar to them. Clement has studied the spontaneous use of analogies in a systematic manner. He investigated, for instance, how novices and experts employ analogies when solving physics problems (Clement, 1978, 1987). The main findings are that both novices and experts frequently make spontaneous use of analogies or at least of comparisons. The studies, therefore, reconfirm that analogies are common tools for explaining and trying to make sense of the unknown.

Empirical Studies on Analogical Reasoning—Ambiguous Results

Empirical studies on analogical reasoning have been carried out both in psychology and science education. Glynn (1989, p. 193) summarized these studies in the field of psychology, stating that "analogical reasoning has been shown to facilitate comprehension and problem solving." Brown and Clement (1987) arrived at a more cautious conclusion. They pointed to the fact that two studies (Gick & Holyoak, 1983; Kaiser et al., 1986) using similar analogies came to quite different conclusions on the effect of analogy use. Indeed, at first sight, the results available are somewhat ambiguous (Gabel & Samuel, 1986; Stepich & Newby, 1988), but they provide hints as to the conditions under which analogical reasoning really occurs.

There is, in fact, substantial support for Glynn's (1989) conclusion that analogical reasoning can facilitate learning and problem solving. Black & Solomon (1987), for instance, investigated students' use of analogies for electric current. They found that the analogies presented helped students to learn. They interpreted this finding from a constructivistic view; analogies were helpful because they allowed the students to construct their own knowledge by forcing them to view the new knowledge within the framework of the analogy. Shapiro (1985) interpreted successful use of analogies in his study, stating that they helped to modify the existing cognitive structure. Gentner and Gentner (1983) reported that analogies aided problem solving in the area of the electric circuit. They further showed that the analogy employed considerably influenced the problem-solving process. They found that problem solving in the area of the electric circuit among college and high school students was considerably different from when a "flowing fluid" or a "moving crowd" analogy was used. These findings point to the fact that the general framework that the analogy provides has a significant influence on the learning process.

Segre and Giani (1987, p. 423) summarized their findings on analogical reasoning about transport processes in the following way: "Our students are almost unable to employ analogical reasoning to solve similar problems regarding different phenomenologies in the field of transport processes." They thought a lack of their students' ability to "formalize" was responsible for their negative results. Clement (1987) reported that attempts to use analogies in learning situations did not work because the learners were not able to "see" the analogy. Research on students' conceptions (see below) supports these findings insofar as areas that are seen as obviously similar by the teacher (or scientist) are viewed as being fundamentally different by many students.

There are several studies indicating that analogies did not work because analogical reasoning did not happen (cf. Enyeart, 1979; Gilbert, 1989; James, 1983; Nägerl, 1980). Gabel and Sherwood (1980) cited further studies indicating that employing analogies was unsuccessful. They interpreted their own negative results by stating that their students were not familiar with the analog domain.

The Multiple Analogies Perspective

There is an aspect in the findings of Gentner and Gentner (1983) presented above that is of general interest for analogy use. "Subjects with the flowing fluid model did better with batteries, while moving objects subjects did better with resistors" (Gentner & Gentner, 1983, p. 118). Dupin and Johsua (1989) reported similar findings concerning learning about electricity, Rumelhart and Norman (1981) where learning about fractions in mathematics is concerned. Analogies usually appear to facilitate or support learning only in specific areas of a target domain. Multiple analogies are, therefore, necessary in order to aid the learning of broader domains. Spiro et al. (1989) viewed the use of multiple analogies from another perspective. They argued that they may function as "antidotes for analogy-induced misconception", i.e., that they may in this way avoid misguidance caused by a single analogy.

Analogical Visuals Can Aid Learning

As has been mentioned above, many analogies facilitate a visualization of the abstract target domain. There are some studies available in which explicitly "visual analogies" are employed, i.e., where pictures, graphics, and the like provide analogies. Dreistadt (1969), for instance, investigated the influence of visual allusions provided on cards during problem solving. A picture of a star, for instance, pointed to the solution in a problem related to the geometrical arrangement of trees. Dreistadt found that such visual allusions had a significant impact. Studies by Shapiro (1985), Royer and Cable (1976), and Rigney and Lutz (1976) also found that analogical visuals may aid learning. One aspect of Dreistadt's (1969) study is of general importance: many of his subjects were *not aware* that the visuals lying in front of them helped them to make progress in their problem-solving process.

Familiarity with the Analog and Access to Analogies

It is quite self-evident that students have to be familiar with the analog domain if analogical reasoning is to be successful. But familiarity is an ambivalent term. Students quite often hold major misconceptions in areas where teachers and textbooks assume familiarity. Although there appears to be no doubt that familiarity with the analog is a necessary prerequisite, it is not sufficient in itself. Gabel and Samuel (1986) found that it was also necessary for students to see the connection between the analog and the target as chemistry problems. Tenney and Gentner (1985, p. 316) summarized findings of studies for water analogies of the electric circuit:

> Increased familiarity with the base domain was not sufficient to ensure the discovery of a potentially useful analogy. However increased familiarity did improve the usefulness of the analogy if detected. The results suggest that familiarity with the base domain affects the power rather than the accessibility of an analogy.

The Learners' Attention Must be Directed Toward the Analogies

"Spontaneous analogical problem solving is not common" summarized Glynn et al. (1989, p. 392), referring to the findings of Gick and Holyoak (1980, 1983) and Holyoak (1985). Seventy-five percent of college students involved in these studies were, for instance, able to solve a story problem by applying previously learned information only after it was suggested to them how they should apply it. Thirty percent of the students could do it without help and 10% without any analogy. A study by Reed et al. (1974) and the one by Tenney and Gentner (1985) already referred to, as well as a study by Hayes and Tierney (1982), have also pointed to the importance of allusions to the analogies to be employed. When taking the studies on spontaneous use of analogies into consideration, it appears legitimate to conclude that spontaneous use of analogy is quite common in everyday life as well as in problem solving, but that the use of fruitful analogies provided by teachers and learning media requires considerable guidance.

Access to Analogies Is Influenced by Both Surface and Higher-Order Similarities

Gentner and Landers (1985) investigated access to analogies. These findings reconfirm on the one hand the above results by Tenney and Gentner (1985) that the inferential power of analogies is governed by similarities of higher-order structure. On the other hand, they found that accessibility is governed by literal or surface similarities but not by similarities from higher-order structures. Holyoak and Koh (1987) also investigated the influence of structural and surface similarities on access to analogies. They found that both similarities are influential but they did not conclude that surface ones govern access. However, they agree with Gentner and Landers (1985) in that only structural similarities affected students' ability to make use of an analog domain once its relevance was pointed out.

The Target Domain Must Be Sufficiently Demanding

It is clear that the "difficulty" of the target domain for the learner is linked with the use of analogies. Royer and Cable (1976) found that analogies were only employed when the target was difficult to understand, i.e., when students felt that it was necessary to look for analogies as an aid to understanding. Gick and Holyoak

(1983) summarized the findings of their studies in a similar way by stating that the target problem must be sufficiently novel and challenging.

Analogy Use and "Ability Level" of the Learner

Sternberg (1977) is of the opinion that there is empirical support for the claim that the ability to reason analogically is closely related to general intelligence. But other studies point out that it depends very much on what is meant by analogical reasoning and general intelligence whether such a point of view is adequate. Enyeart (1979), for instance, found no general correlation between analogy use and Piagetian levels. There was only a significant correlation between the use of formal analogies (i.e., analogies representing proportions) and formal operational thought.

There are also studies that investigated the use of analogies for students at different levels of ability. Gabel and Sherwood (1980) reported a tendency for their analogies to be more effective for students of lower formal reasoning ability and not especially useful for more capable students. It seems clear that this has to do with the aspect mentioned above (cf. Royer & Cable, 1976; Gick & Holyoak, 1983) that the target has to be sufficiently difficult and challenging for the learner. Sutala and Krajcik's (1988) study points in a similar direction. They found that students with high cognitive abilities benefited more from creating their own analogical connections, whereas students with low abilities benefited more from having the teacher help them make the analogical connection.

Research Findings in the Area of Students' Conceptions

Empirical research on students' scientific conceptions has been given much attention in the past 15 years (see the bibliography by Pfundt & Duit, 1991). Some main findings of importance for analogy use will be summarized in the following sections.

It cannot at all be taken for granted, for instance, that a concept that is already taught may be used as an analog because students often still hold major misconceptions (viewed from the target perspective) that make them unable to understand the analogy drawn. Studies on students' conceptions of the water analogy (cf. Gentner & Gentner, 1983; Schwedes & Schilling, 1983) highlight this aspect. They showed that many misconceptions known from research on students' conceptions of the electric circuit were held by their students in the case of the water circuit too. If this is also true for other domains used as analogs—and there appears to be no doubt that this quite often will be the case—analogical reasoning often will not be able to remedy students' misconceptions, but rather will support them.

Furthermore, content areas that are very similar or even identical viewed from the scientific perspective may be seen in totally different ways by students. Claxton (n.d.) highlights this by his term "mini-theories." Students' conceptions usually have only a rather limited range. Students' conceptions of heat transfer may serve as an example (cf. Tiberghien, 1983). Processes the physicist uniformly describes in the framework of heat conduction were viewed considerably differently by students depending on the context in which heat transfer occurred.

Findings of cognitive conflict strategies used to "remedy" students' misconceptions (see the summary in Driver & Erickson, 1983) are also of interest here. Generally speaking, the strategies very often did not work because the students were unable to "see" the conflict, or to put it in other words, there was no conflict viewed from the students' perspective.

RESEARCH ON ANALOGY USE IN TEXTBOOKS AND IN THE CLASSROOM

Whereas there is a number of empirical studies on how analogies may work in learning, only little is known about the actual use of analogies both in textbooks and in classrooms.

The Use of Analogies in Textbooks

Glynn et al. (1989) examined analogy use in an analysis of 43 elementary, high school, and college science textbooks. The analysis was of an interpretive nature, i.e., it was not based on formally developed categories. Glynn et al. found many examples of simple analogies such as "mitochondria are the powerhouse of the cell" in textbooks. Elaborate analogies, which were a paragraph or even a page long, were relatively rare. High school physics and physical science books appeared to contain the largest number of such elaborate analogies. The frequency of analogies in the 19 physics and physical science books varied between relatively extensive and little use. There is another interesting observation. Although it was common in the introduction to provide the reader with hints as to how to use the textbooks effectively (e.g., hints about advance organizers) no mention of analogies was found there—not even in the textboks in which excellent use of analogies was made.

Curtis and Reigeluth (1984) analyzed analogy use in 26 science textbooks. Their analysis was much more quantitative than that of Glynn et al. (1989). The use of analogies according to several categories (such as type of analogy or placement) was investigated. In total, 216 analogies were found, i.e., 8.3 analogies per book (ranging from zero to 18). Two main types of analogy were distinguished, namely, simpler ones based mainly on surface similarities and more elaborate ones based on what Curtis and Reigeluth called "functional relationships." In total, most analogies were of the latter kind (70%). Whereas this number was less than 50% in elementary books, it was substantially higher in chemistry and physics books (about 90%). This result points in a similar direction to that of Glynn et al. (1989) who found that elaborate analogies were most often used in physics textbooks. It is interesting that in about 50% of the 216 analogies, the authors made no attempt to describe the analog or how to strategically use the analogies provided. There are similar findings in the study of Glynn et al. (1989); guidance toward effective use of analogies was not explicitly given in the introduction of the textbooks. Curtis and Reigeluth (1984) drew several conclusions from their study that may help to produce powerful analogies. They point out that analogies appear to be most useful for complex and difficult content. They view simpler analogies that are mainly based on surface similarities as only suitable for easier, more concrete topics, whereas more difficult and abstract topics require functional analogies, i.e., analogies based on deep structure similarities.

The Use of Analogies in Classrooms

Little is known about how analogies are used in classrooms. Tierney (1988) observed four social studies teachers for 20 lessons. He focused on "small scale" comparisons (use of metaphors, analogies, and similes as example, or reinforcement of verbal or written explanation of content) used in history lessons. Such comparisons were often employed but mostly in a limited manner: "Like comedians, these teachers went with what worked. It was clear that simply telling the story of history was insufficient. Seldom did the teachers stop to check specifically that students understood the metaphors used" (Tierney, 1988, p. 13). Very much like analogies used by authors in textbooks, the teachers observed by Tierney (1988) appeared to presuppose that students were familiar with the analog domain and would use the metaphors, analogies, or similes without any guidance.

In a study by Treagust et al. (1990), limited analogy use is also reported. Forty lessons by eight science teachers were observed. The study was carried out within an interpretive research framework (Erickson, 1986). Field notes of lessons and an interview with every teacher at the end of the observation period formed the basis of interpretation. Use of analogies based on structural relationships (rather than surface similarities) was the focus of the study. The teachers in this study seldom used such analogies in their teaching (in the 40 lessons observed, only eight of them were detected) and tended not to use them in an elaborated manner even when such analogies were present in the textbook used by the class. This finding seemingly contradicts the results of the interviews, which revealed that most teachers were very aware of both the benefits and limitations of analogies. But the teachers in the study seemed not to have a repertoire of good analogies and were not confident concerning the effective use of analogy. Where the broader context of analogy use within a constructivistic learning perspective is concerned, the study points out that the teachers mainly held traditional views of the learning process. Accordingly analogy use—if it occurred—was not based on a constructivistic approach to learning.

Analogy Use in Textbooks and in the Classroom—Limited in Various Ways

Research available so far in this field revealed major limitations of analogy use in textbooks as well as in classroom practice. It is notable that it is very often simply taken for granted that analogies are used by the readers (students) in the intended way without any further guidance. Research findings presented above highlight that this is very often not true, that considerable guidance concerning the use of analogy in a fruitful manner is necessary, and that frequently students are not familiar with the analog domain or are familiar with it in a misleading way. Another aspect became visible, namely, that the repertoire of good analogies some textbook authors and teachers possess appears to be limited. Furthermore, strategies concerning effective use of analogies did not seem to be known to many authors of textbooks and teachers. The empirical evidence on which the findings summarized here are based is small. Further studies must be carried out. These studies should include actual analogy use as well as the development of new strategies.

APPROACHES TO ANALOGY USE IN TEACHING SCIENCE

There is a number of articles available providing approaches to analogy use in teaching and learning science. Some have already been cited in the preceding sections. Others will contribute to the summary presented in the next section. In the present section, four elaborated approaches will be discussed.

The Structure Mapping Theory

This theory starts from the idea that "a relational structure that normally applies in one domain can be applied in another domain" (Gentner, 1983, p. 156). It is based on theories of propositional networks as, for instance, described by Rumelhart and Ortony (1977). There are many major similarities with the general framework presented in Figure 1. Gentner (1988) distinguishes four kinds of similarities:

1. *Analogy.* Only (or at least mainly) relational predicates are mapped and no (or very few) object attributes.
2. *Literal similarity.* Both relational predicates and object attributes are mapped.
3. *Relational abstraction.* Abstract relational structures of a base domain are mapped. There are no concrete properties of objects to be left behind in the mapping.
4. *Mere-appearance match.* Chiefly object descriptions are mapped.

There are no strict distinctions between the kinds of similarities. Viewed within the framework presented in Figure 1 there is, for instance, no principal difference between analogies and relational abstractions. The latter are viewed as analogies of a higher level.

Relational abstractions are said to possess the most inferential power in the learning process. Literal similarities are viewed as much less valuable in this respect, and mere-appearance matches as of almost no value. But access is much more likely with literal similarities and mere-appearance matches. Analogies are somewhere between literal similarities and relational abstractions. On the one hand, they facilitate the implementation of high inferential power because mainly relational structures are mapped; on the other hand, object attributes may ease access to the analogies (see what has been discussed concerning the importance of surface attributes above).

An important principle of the structure-mapping theory is the systematicity principle (Gentner, 1983, p. 163): "a predicate that belongs to a mapable system of mutually interconnecting relationships is more likely to be imparted into the target than an isolated predicate."

Comments on the Structure Mapping Theory

The structure mapping theory is mainly designed from a psychological point of view. But applications for science teaching are already "prepared" in that many examples presented in Gentner's papers are from that knowledge domain, especially from physics (e.g., concerning the electric circuit or heat). The very careful analysis (as, for instance, presented in Forbus & Gentner, 1986 or in Gentner & Gentner, 1983) may serve as paradigms for science educators when designing analogies. There are several aspects of the theory that are of potentially high value in this process. The distinction of the above-mentioned kinds of similarities may help to design "true" analogies with high inferential power and not simply literal similarities or even mere-appearance matches. The systematicity principle points to the fact that an analogy should map substantial parts of target domain structures and not merely single aspects.

The General Model of Analogy Teaching (GMAT)

Zeitoun (1984) has developed a model for analogy use. The model is based on schema theory as presented by Rumelhart and Norman (1981). But it also contains several quite pragmatic considerations.

The model comprises 9 stages (see Figure 2). The first one is optional. In fact, there is not enough research available so far to really take this aspect into consideration. Stage 2 is essential in the planning of learning processes seen from a constructivistic point of view; what the learner already knows about what has to be learned (here called topic) is of pivotal importance. Stage 3 analyzes whether the teaching materials available already contain analogies or whether new ones must be designed. Main aspects in the following stage are familiarity and complexity of the analogies. The latter gives priority to analogies providing many analogous attributes [compare Gentner's systematicity principle (1983)]. The following stages appear to be valid for planning learning in general. However, some specific aspects of analogy use are included.

Comments on the GMAT

Zeitoun (1984) summarizes the relevant literature in his article and transfers some main findings to his model. However, the model appears to have some limitations. First, the general setup is quite pragmatic and seems to lack major aspects of the theoretical basis, which is developed in the first part of the paper. Second, some important aspects of analogy use are not shown in the model. The

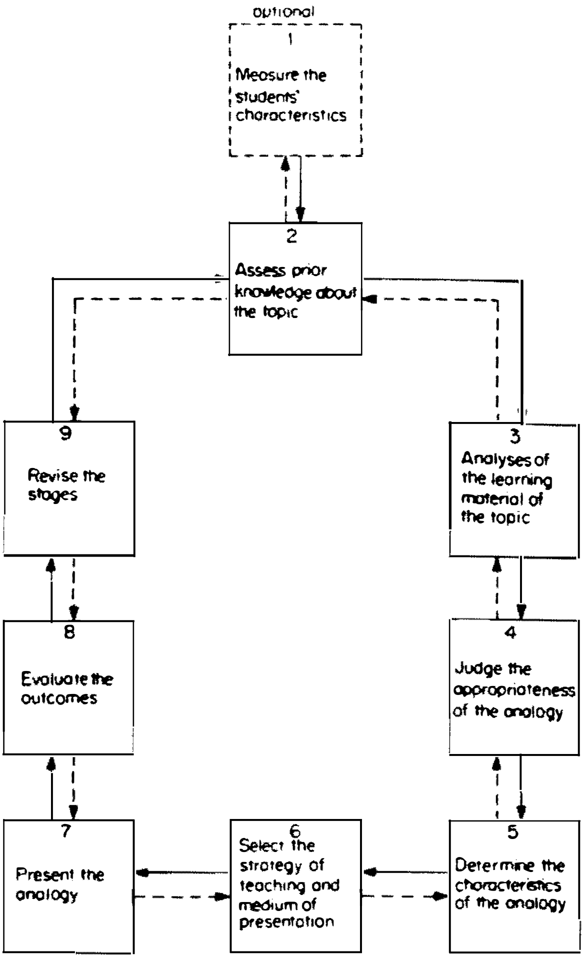

Figure 2. Stages of Zeitoun's GMAT (1984)

importance of prior knowledge, for instance, is only dealt with in a somewhat vague manner. What is essential with regard to analogies is to make sure whether prior knowledge of the analog domain allows for fruitful analogies or whether the analogies may transfer severe misconceptions from analog to target (Zeitoun calls this domain "topic"). Third, the article contains only a limited number of examples allowing a judgment as to whether the model may facilitate a fruitful planning process.

The TWA (Teaching-with-Analogy) Model

Coming from a research perspective of text comprehension a group at the University of Georgia (cf. Glynn, 1989, 1991; Glynn et al., 1989) have investigated the value of analogies used by textbook authors (see also the preceding section). They have developed a valuable framework for analogy use in science teaching.

They take a constructivistic position. Their proposals are, therefore, very much in accordance with what has been worked out in the previous sections of this paper. Some main features of their work will be discussed here.

Explanatory and Creative Function of Analogy Use. An analogy "serves an explanatory function when it puts new concepts and principles into familiar terms. It serves a creative function when it stimulates the solution of existing problems, the identification of new problems and the generation of hypotheses" (Glynn et al., 1989, p. 383). These functions are very much in accordance with what has been discussed about the role of analogies in the learning process above. The examples Glynn et al. (1989) provide may give the rather abstract considerations there a more "concrete" meaning.

Search for the Superordinate Concept. Another important idea concerns the value of looking for the superordinate concept, which can be applied to both the analog and the target. Water circuits and electric circuits, for instance, both are circuits. Glynn et al. (1989, p. 385) see some "creative" function in such searches for the superordinate: "The identification and naming of the superordinate concept can suggest analogies, it also can stimulate students to generalize what they have learned and apply their learning to other concepts."

The TWA Model. The TWA model has been developed on the basis of theoretical considerations concerning analogy use, empirical studies on analogical reasoning and an analytical study about analogy use in physics textbooks (see above). The TWA model (Glynn, 1989, p. 198) contains the following six operations:

1. Introduce target concept.
2. Recall analog concept.
3. Identify similar features of concepts.
4. Map similar features.
5. Draw conclusions about concepts.
6. Indicate where analogy breaks down.

Comments on the TWA Model

The model undoubtedly is of great help when using analogies in teaching. But it only provides a general structure, a proposal of steps to be followed. How these steps are taken is the essential issue—and Glynn et al. (1989) are aware of this. It has to be done in the above-developed "spirit" if analogies are to be of real use. Furthermore, in steps 2–5 it should be kept in mind that it is necessary to make sure that students understand the analogy in the way the teacher thinks they should and to ensure that students really see the similarities the teacher has in mind.

Remarks on Other Guidelines for Effective Analogy Use

The models of analogy use discussed above in this section provide valuable hints as to how to develop and effectively introduce analogies in textbooks and in classroom teaching. There are further suggestions of this kind in literature, which are usually based on facets of research presented above (cf. Curtis & Reigeluth, 1984; Keane, 1987; Radford, 1989; Stepich & Newby, 1988). Strategies concerning how to find appropriate analog domains are proposed as are guidelines for placing analogies and for guiding readers or students toward effective use.

The "Bridging Analogies" Approach

Clement and a group of colleagues at the University of Massachusetts have developed a promising approach to "remedying" students' misconceptions via what they call "bridging analogies" (cf. Brown & Clement, 1987, 1989; Clement, 1987). Their work starts from research findings in the area of students' conceptions mentioned above. There is, for instance, an abundance of empirical evidence that analogy use often fails because (1) students do not understand the analog properly; and (2) students are not able to draw the analogies intended.

Anchors and Bridges. The main idea of the "bridging analogies" approach is based on the two deficiencies mentioned. Clement and his colleagues therefore very carefully searched for analog situations that trigger a correct intuition, i.e., an intuition that can be developed toward understanding the target situation (a similar starting point is taken by Stavy, 1991). They call these analogs "anchors" (or "anchoring examples"). But even if analogy teaching starts from analogs familiar to students, it often fails because the "jump" (so to speak) from the analog to the target is too big. The big jump is, therefore, split into smaller ones that can be mastered.

An Example of the Bridging Analogy Approach. "A book is lying on a table" (see Figure 3, right side). It is well known from students' conceptions research that most students have severe difficulties in comprehending that the table "pushes up" the book, i.e., that the table is acting on the book via a force. According to these students, forces are attached mainly to active things. The table is not active, hence, there is no force on the book caused by the table. To guide the students toward understanding the target situation, namely, that there is an upward force acting on the book due to the action of the table, they start with the situation shown on the left side of Figure 3. A spring is compressed by a finger. In this case, there is obviously (according to Brown & Clement, 1989) a force acting on the finger caused by the spring. This situation, therefore, triggers the correct intuition. From this anchoring situation, they proceed toward the target situation via two bridging situations, namely, a book lying on foam and a book lying on a thin board. A visualization in the particle model (Figure 3) is employed to further support the bridging analogies.

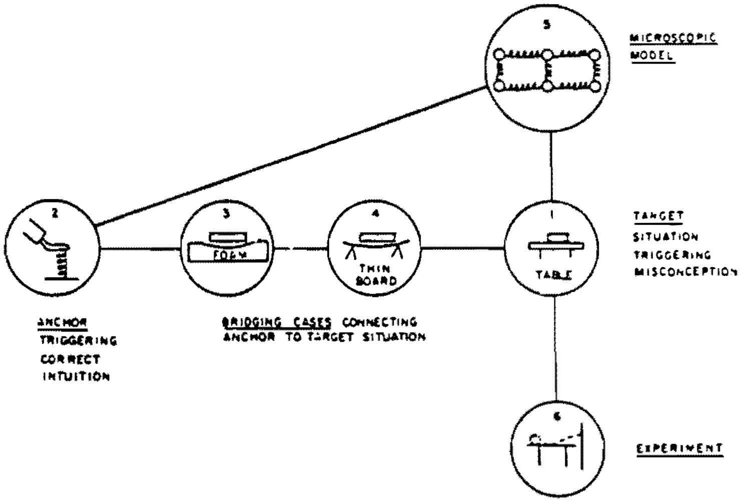

Figure 3. An example of bridging analogies (from Clement, 1987).

Comments on the "Bridging Analogies" Approach

The approach is still being developed, but the research results on its value so far available are promising. It is necessary to point out that it is not simply the idea of building bridges starting from an anchoring situation that essentially constitutes the approach. The approach is deliberately based on a constructivistic framework. The teaching strategy used is therefore very student-oriented, involves main aspects of negotiation of views, and employs aspects of socratic dialogue.

A main problem with the apporach is that there may be not enough good anchoring situations and bridging analogies available. We know from research on students' conceptions that students' ideas in many fields are different from scientific views. It cannot, therefore, be taken for granted that anchoring situations can be found. Quite often it appears that these situations have to be "created" by developing students' alternative ideas in the analog domain via conceptual change learning. This may also be true of the anchoring situation used in Figure 3. Not all students (especially younger ones) will intuitively trigger the correct idea that the spring is acting back on the finger because the finger is the active partner in their view, not the spring (see related research findings summarized by Driver, 1985 or McDermott, 1983).

ON ANALOGY USE IN TEACHING AND LEARNING SCIENCE—A CONCLUDING VIEW

Analogy use will be summarized against the background of the perspectives underlying this paper, namely the view of metaphorical aspects of analogies and the constructivistic view of learning.

What is an Analogy?

An analogy is—in the framework of this paper (see Figure 1)—a relation between parts of the structures of two domains. Hence, an analogy may be viewed as a statement of comparison on the basis of similarities between the structures of two domains. "Simple" comparison statements pointing only to somewhat superficial similarities are not seen as analogies in this study. But many simple comparisons may be developed into analogies.

Advantages of Analogies

According to a constructivistic view of learning, it is essential that similarities between the knowledge to be acquired and what is already known be drawn. Analogies are powerful tools to facilitate the learners' construction process on the grounds of concepts that are already available. The advantages of analogies are due to their significance within a constructivistic perspective of learning. These advantages include:

1. They are valuable tools in conceptual change learning, which open new perspectives.
2. They may facilitate an understanding of the abstract by pointing to similarities in the real world.
3. They may provide visualization of the abstract.
4. They may provoke students' interest and may therefore motivate them (compare the metaphorical aspects discussed below).

There is another advantage within the constructivistic planning of learning:

5. They force the teacher to take students' prior knowledge into consideration. Analogy use may also reveal misconceptions in areas already taught.

Disadvantages and Potential Dangers of Analogies

Analogies are "double-edged swords" (Glynn et al., 1989, p. 387), which may totally mislead. It is important to note:

1. An analogy is never based on an exact fit between analog and target. There are always features of analog structure that are different from those of the target. These features may mislead.
2. Analogical reasoning is only possible if the intended analogies really are drawn by the students. If students hold misconceptions in the analog domain analogical reasoning will transfer them into the target domain. It is therefore important to ensure that the intended analogies really are drawn by the students.
3. Although analogical reasoning appears to be quite common both in daily life and in other contexts, spontaneous use of analogies provided by teachers or learning media seldom happens. Analogical reasoning in learning situa-

tions requires considerable guidance. Access to the analogies provided is facilitated by surface similarities and by deep structure aspects. But only the deep structure aspects have inferential power.

The "From-Metaphor-to-Analogies" Approach—On Metaphorical Aspects of Analogies

Every analogy has some points in common with metaphors. It appears to be of great advantage to employ these aspects in the learning process. They may motivate students because they point to some anomaly or cause some surprise. In some circumstances it may be valuable to follow a "from-metaphor-to-analogy" approach. This means that a metaphorical statement opens teaching in order to provoke students' thought by its seemingly paradoxical meaning. "Photosynthesis is mother nature's way of baking a cake" (a metaphorical version of an analogy outlined in Glynn, 1989) is in fact a surprising statement. But it may be of value and fruitful to students to find out how it makes sense.

The Two-Way Aspect of Analogies

Analogy relations between analog and target are basically symmetrical, i.e., analogy and target can change roles. In every use of analogy, both analog and target are developed. Learning to "see" the target from the perspective of the analog also provides new views of the latter. Hence, teaching strategies are possible that switch the roles of analog and target to further develop two domains already established to a certain extent. In the study by Treagust et al. (1990), there is an example of such a strategy. While introducing the electrical field, a teacher drew analogies to the gravitational field, which was known (to a certain extent) to the students already. He changed the role of analog and target several times, that is, he not only used the gravitational field to work out features of the electrical field but also employed the electrical field to highlight features of the gravitational field.

Multiple Analogies

Analogies usually only aid learning in specific areas of target domains. Hence, multiple analogies are necessary in order to facilitate learning of the whole domains.

The Systematicity Principle

Analogies are powerful tools in learning only if they map onto considerable parts of structures. Single, isolated features of structures are of much less value because it is less likely that they can be incorporated into the target, according to Gentner's (1983) principle.

Personal Analogies

Students put themselves into a situation, e.g., they imagine that they are particles hit by other particles. Such personal analogies appear to be very well suited to making the target domain familiar. But they are also in great danger of misleading because they appeal to intuitive feeling.

The Role of Analogies and Metaphors in Science as a Topic of Science Instruction

The role of analogies and metaphors in science instruction is usually discussed from the perspective of their significance in the learning process, but there is another important aspect. Analogies and metaphors serve significant explanatory and heuristic functions in the development of science (cf. Hesse, 1966; Leatherdale, 1974). If it is accepted that science instruction should not only teach scientific knowledge but also scientific metaknowledge, then the role of analogies and metaphors in science must be considered to be an essential aspect of science instruction.

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References

Bauer, F., & Richter, V. (1986). Möglichkeiten und Grenzen der Nutzung von Analogien und Analogieschlüssen. *Physik in der Schule, 24*, 384–389.

Berlyn, D. E. (1966). *Structure and direction in thinking.* New York: Wiley.

Black, M. (1979). More about metaphor. In A. Ortony, *Metaphor and thought.* Cambridge: Cambridge University Press, 19–43.

Black, D., & Solomon, J. (1987). Can pupils use taught analogies for electric current? *School Science Review, 69*, 249–254.

Brown, D. E., & Clement, J. (1987). *●vercoming misconceptions in mechanics: A comparison of two example-based teaching strategies.* Paper presented at the Annual Meeting of the American Educational Research Association, Washington, DC.

Brown, D. E., & Clement, J. (1989). Overcoming misconceptions via analogical reasoning: Abstract transfer versus explanatory model construction. *Instructional Science, 18*, 237–261.

Bunge, M. (1973). *Method, model and matter.* Dordrecht, Boston: D. Reidel Publishing Company.

Claxton, G. L. (n.d.). *Teaching and acquiring scientific knowledge.* Centre for Science and Mathematics Education, King's College, University of London.

Clement, J. (1978). *The role of analogy in scientific thinking: Examples from a problem solving interview.* University of Massachusetts, Department of Physics and Astronomy.

Clement, J. (1987). Overcoming students' misconceptions in physics: The role of anchoring intuitions and analogical validity. In J. Novak (Ed.), *Proceedings of the 2nd International Seminar Misconceptions and Educational Strategies in Science and Mathematics.* Ithaca, NY: Cornell University Press, vol. 3, 84–97.

Curtis, R. V., & Reigeluth, C. M. (1984). The use of analogies in written text. *Instructional Science, 13,* 99–117.

Davidson, R. D. (1976). The role of metaphor and analogy in learning. In J. R. Levin & V. L. Allen (Eds.), *Cognitive learning in children: Theories and strategies.* New York: Academic Press, 135–162.

Dreistadt, R. (1969). The use of analogies and incubation in obtaining insight in creative problem solving. *The Journal of Psychology, 71,* 159–175.

Driver, R. (1985). Cognitive psychology and pupil's frameworks in mechanics. In P. Lijnse (Ed.), *The many faces of teaching and learning mechanics.* Utrecht: GIREP/SVO/UNESCO, 171–198.

Driver, R., & Erickson, G. (1983). Theories in action: Some theoretical and empirical issues in the study of students' conceptual frameworks in science. *Studies in Science Education, 10,* 37–60.

Duit, R. (1991). Students' conceptual frameworks: Consequences for learning science. In S. Glynn, R. Yeany, & B. Bitton (Eds.), *The psychology of learning science.* Hillsdale, NJ: Erlbaum, 65–85.

Dupin, J. J., & Johsua, S. (1989). Analogies and "modeling analogies" in teaching: Some examples in basic electricity. *Science Education, 73,* 207–224.

Enyeart, M. A. (1979). *Analogy and physics achievement.* Paper presented to the fifty-second annual meeting of the National Association for Research in Science Teaching, Atlanta, GA.

Erickson, F. (1986). Qualitative methods in research on teaching. In M. Wittrock (Ed.), *Handbook of research on teaching* (3rd ed.). New York: Macmillan, 119–161.

Festinger, L. (1962). *A theory of cognitive dissonance.* Stanford: Stanford University Press.

Forbus, K. D., & Gentner, D. (1986). Learning physical domains: Toward a theoretical framework. In R. S. Michalski, J. G. Carbonell, & T. M. Mitchell (Eds.), *Machine learning: An artificial intelligence approach.* Los Altos, CA: Morgan Kaufmann, vol. 2, 311–348.

Fraser, B. J., & Rennie, L. J. (1988). *Learning in science: Qualitative and quantitative investigations in year 10 classrooms.* Paper presented at the Annual Conference of the Australian Science Education Research Association, Sydney.

Gabel, D. L., & Samuel, K. V. (1986). High school students' ability to solve molarity problems and their analog counterparts. *Journal of Research in Science Teaching, 23,* 165–176.

Gabel, D., & Sherwood, R. D. (1980). Effect of using analogies on chemistry achievement according to Piagetian level. *Science Education, 64,* 709–716.

Gagne, R. M. (1970). *The conditions of learning.* New York: Holt, Rinehart, & Winston.

Gee, B. (1978). Models as a pedagogical tool: Can we learn from Maxwell? *Physics Education, 13,* 1978.

Gentner, D. (1983). Structure-mapping: A theoretical framework for analogy. *Cognitive Science, 7,* 155–170.

Gentner, D. (1988). Analogical inference and analogical access. In A. Prieditis (Ed.), *Analogica.* Los Altos, CA: Morgan Kaufmann, 63–88.

Gentner, D., & Genter, D. R. (1983). Flowing waters or teaming crowd: Mental models of electricity. In D. Gentner & A. L. Stevens (Eds.), *Mental models.* Hillsdale, NJ: Erlbaum, 99–129.

Gentner, D., & Landers, R. (1985). *Analogical reminding: A good match is hard to find.* Paper presented at the International Conference on Systems, Man, and Cybernetics, Tuscon, AZ.
Gick, M. L. & Holyoak, K. J. (1980). Analogical problem solving. *Cognitive Psychology, 12,* 306–355.
Gick, M. L., & Holyoak, K. J. (1983). Schema induction and analogical transfer. *Cognitive Psychology, 15,* 1–38.
Gilbert, S. W. (1989). An evaluation of the use of analogy, simile and metaphor in science texts. *Journal of Research in Science Teaching, 26,* 315–327.
Glynn, S. M. (1989). The teaching with analogies model: Explaining concepts in expository texts. In K. D. Muth (Ed.), *Children's comprehension of narrative and expository text: Research into practice.* Neward, DE: International Reading Association, 185–204.
Glynn, S. M. (1991). Explaining science concepts: A teaching-with-analogies-model. In S. Glynn, R. Yeany, & B. Britton (Eds.), *The psychology of learning science.* Hillsdale, NJ: Erlbaum, 219–240.
Glynn, S. M., Britton, B. K., Semrud-Clikeman, M., & Muth, K. D. (1989). Analogical reasoning and problem solving in science textbooks. In J. A. Glover, R. R. Ronning, & C. R. Reynolds (Eds.), *A handbook of creativity: Assessment, research and theory.* New York: Plenum.
Göbel, R. (1976). Der Analogieschluβ. *Physik in der Schule, 14,* 86–94.
Gowin, D. B. (1983). Metaphors and conceptual change: Once more with feeling. In H. Helm & J. Novak (Eds.), *Proceedings of the International Seminar Misconceptions in Science and Mathematics.* Ithaca, NY: Cornell University, 38–41.
Hayes, D. A. & Tierney, R. J. (1982). Developing readers' knowledge through analogy. *Reading Research Quarterly, 17,* 256–280.
Hesse, M. (1966). *Models and analogies in science.* Notre Dame, IN: The University of Notre Dame Press.
Holyoak, K. J. (1985). The pragmatics of analogical transfer. In G. H. Bower, *The psychology of learning and motivation.* Orlando, FL: Academic Press, vol. 19.
Holyoak, K. J., & Koh, K. (1987). Surface and structural similarity in analogical transfer. *Memory and Cognition, 14,* 332–340.
Howard, R. (1989). Teaching science with metaphors. *School Science Review, 70,* 100–103.
James, M. (1983). The use of a specific model in the teaching of a scientific concept. *The Australian Science Teachers Journal, 29(2),* 9–17.
Kaiser, M. K., Jonides, J., & Alexander, J. (1986). Intuitive reasoning about abstract and familiar physics problems. *Memory and Cognition, 14,* 308–312.
Keane, M. (1987). Cognitive theory of analogy. In T. Richardson, M. Eysenck, & D. Piper (Eds.), *Student learning.* Hillsdale, NJ: Erlbaum, 66–72.
Kelly, G. (1955). *The psychology of personal constructs.* New York: Norton.
Kircher, E. (1989). Analogien im Physikunterricht. In W. Schneider (Ed.), *Wege in die Physikdidaktik.* Erlangen: Palm und Enke, 47–57.
Klinger, W. (1987). Die Rolle der Analogiebildung bei der Deutung physikalischer Phänomene. In W. Kuhn (Ed.), *Didaktik der Physik. Vorträge der Frühjahrstagung in Berlin 1987.* Gieβen: DPG Fachausschuβ Didaktik der Physik, 326–333.
Kuhn, T. S. (1970). *The structure of scientific revolutions.* Chicago: University of Chicago Press.
Leatherdale, W. H. (1974). *The role of analogy, model and metaphor in science.* Amsterdam: North-Holland Publication Company.
Lind, G. (1980). Models in physics: Some pedagogical reflections based on the history of science. *European Journal of Science Education, 2,* 15–23.

McDermott, L. (1983). Critical review of research in the domain of mechanics. *Research on Physics Education: Proceedings of the First International Workshop.* La Londe les Maures, 139–182.

Miller, G. A. (1979). Images and models, similes and metaphors. In A. Ortony (Ed.), *Metaphor and thought.* Cambridge: Cambridge University Press, 202–250.

Muscari, P. G. (1988). The metaphor in science and in the science classroom. *Science Education, 72,* 423–431.

Nägerl, H. (1980). Transfer mittels Analogie: Lernhilfe bei der Informationsverarbeitung. In A. Scharmann & A. Hofstaetter (Eds.), *DPG Fachausschuß Didaktik der Physik. Vorträge der Frühjahrstagung 1980.* Gießen: 1. Physikalisches Institut, 501–506.

Paivio, A. (1983). The mind's eye in arts and science. *Poetics, 12(1),* 1–18.

Pfundt, H., & Duit, R. (1991). *Bibliography students' alternative conceptions and science education.* Kiel: IPN.

Piaget. J. (1953). *The origin of intelligence in the child.* London: Routledge & Kegan.

Radford, D. L. (1989). *Promoting learning through the use of analogies in high school biology textbooks.* Paper presented at The Annual Meeting of the National Association of Research in Science Teaching, San Francisco.

Reed, S. K., Ernst, G. W., & Banerji, R. (1974). The role of analogy in transfer between similar problem states. *Cognitive Psychology, 6,* 436–450.

Rigney, J. W., & Lutz, K. A. (1976). Effect of graphic analogies of concepts in chemistry on learning and attitude. *Journal of Educational Psychology, 68,* 305–311.

Royer, J. M., & Cable, G. W. (1976). Illustrations. analogies and facilitative transfer in prose learning. *Journal of Educational Psychology, 68,* 205–209.

Rumelhart, D. E., & Normann, D. A. (1981). Analogical processes in learning. In J. R. Anderson (Ed.), *Cognitive skills and their acquisition.* Hillsdale, NJ: Erlbaum, 335–359.

Rumelhart, D. E., & Ortony, A. (1977). Representation of knowledge. In J. R. Anderson, R. J. Spiro, & W. E. Montague (Eds.), *Schooling and the acquisition of knowledge.* Hillsdale, NJ: Erlbaum.

Schwedes, H., & Schilling, P. (1983). Schülervorstellungen zu Wasserstromkreisen. *Physica didactica, 10,* 159–170.

Segre, G., & Giani, U. (1987). Analogical reasoning and formalization in transport processes. In J. Novak (Ed.), *Proceedings of the 2nd International Seminar Misconceptions and Educational Strategies in Science and Mathematics.* Ithaca, NY: Cornell University, vol. 1, 420–424.

Shapiro, M. A. (1985, May). *Analogies, visualization and mental processing of science stories.* Paper presented to the Information Systems Division of the International Communication Association.

Spiro, R. J., Feltovich, P. J., Coulson, R. L., & Anderson, D. K. (1989). Multiple analogies for complex concepts: Antidotes for analogy-induced misconception in advanced knowledge acquisition. In S. Vosniadou & A. Ortony (Eds.), *Similarity and analogical reasoning.* Cambridge: Cambridge University Press, 498–531.

Stavy, R. (1991). Using analogy to overcome misconceptions about conservation of matter. *Journal of Research in Science Teaching,* 305–313.

Steiner, H. G. (1988). Über Metaphern, Modelle und Mathematik. In P. Bender (Ed.), *Mathematikdidaktik—Theorie und Praxis. Festschrift für Heinrich Winter.* Berlin, 190–201.

Stepich, D. A., & Newby, T. J. (1988). Analogical instruction within the information processing paradigm: Effective means to facilitate learning. *Instructional Science, 17,* 129–144.

Sternberg, R. J. (1977). Component processes in analogical reasoning. *Psychological Review, 84*, 353–378.
Sutala, V., & Krajcik, J. S. (1988). *The effective use of analogies for solving mole problems in high school chemistry*. Paper presented at the Annual Meeting of the National Association of Research in Science Teaching.
Sutton, C. (1978). *Metaphorically speaking—The role of metaphor in teaching and learning science*. Science Education Series. University of Leicester, School of Education.
Sutton, C. (1981). Metaphorical imagery—A means of coping with complex and unfamiliar information in science. *Durham and Newcastle Research Review, 4*, 216–222.
Tenney, Y., & Gentner, D. (1985). What makes analogies accessable: Experiments on the water-flow analogy for electricity. In R. Duit, W. Jung, & C. von Rhöneck (Eds.), *Aspects of understanding electricity*. Kiel: IPN/Schmidt & Klaunig, 311–318.
Tiberghien, A. (1983). Critical review on the research aimed at elucidating the sense that notions of temperature and heat have for the students aged 10 to 16 years. *Research on physics education. Proceedings of the first international workshop*. La Londe les Maures, 75–90.
Tierney, D. S. (1988). *How teachers explain things: Metaphoric representation of social studies concepts*. Paper presented at the Annual Meeting of the American Educational Research Association.
Treagust, D. F., Duit, R., Joslin, P., & Lindauer, I. (1990). *A naturalistic study of science teachers' use of analogies as part of their regular teaching*. Paper presented at the Annual Meeting of the American Educational Research Association, Boston.
von Glasersfeld, E. (1983). Learning as a constructivistic activity. In J. C. Bergeron & N. Hevscovics (Eds.), *Proceedings of the 5th annual meeting of the PME-NA, Montreal*. 41–69.
Webb, M. J. (1985). Analogies and their limitations. *School Science and Mathematics, 85*, 645–650.
Weller, C. M. (1970). The role of analogy in teaching science. *Journal of Research in Science Teaching, 7*, 113–119.
West, L., & Pines, L. (1985). *Cognitive structure and conceptual change*. Orlando, FL: Academic Press.
Wittrock, M. (1985). Learning science by generating new conceptions from old ideas. In L. West & L. Pines (Eds.), *Cognitive structure and conceptual change*. Orlando, FL: Academic Press, 259–266.
Zeitoun, H. H. (1984). Teaching scientific analogies: A proposed model. *Research in Science and Technology Education, 2*, 107–125.

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