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17. USE OF ANALOGY AND COMPARATIVE THINKING IN SCIENTIFIC CREATIVITY AND GIFTED EDUCATION

IMPORTANCE OF COMPARATIVE THINKING

Fundamental Cognitive Processes

Discerning similarities and differences are fundamental cognitive operations for learning. Four important strategies for engaging students in using these foundational operations (Marzano, Pickering, & Pollock, 2001) are (1) comparing similarities and contrasting differences; (2) classifying things into categories based on characteristics; (3) creating analogies that map relationships between pairs of concepts; and (4) creating metaphors that show similar patterns from different domains. A meta-analysis (Apthorp, Dean, & Igel, 2012) of twelve studies from 1998 to 2008 that focused on using similarities and differences, such as analogy, with kindergarten through high school students, indicated that these approaches positively influence student learning. Larger effect sizes were seen when the control group experienced traditional teacher-directed, textbook-based instruction with smaller effects when the control also involved interactive teaching strategies. Student learning improved with the opportunity to reflect and discuss including the systematic guidance of students through analogical reasoning and classification of important concepts along with relationships among and between concepts.

Metaphors, Similes, and Analogies

There are several types of comparisons that people utilize to comprehend new concepts. A *metaphor* is a literary device or figure of speech that is substituted for the concept being examined in order to draw the mind to recognize a resemblance between the two. *Similes* are comparisons that use the words "like" or "as," but generally do not carry as much feeling as metaphors. For instance, saying, "The lion is king" has a stronger emotional impact than "The lion is like a king." Metaphors are often found in poetry and usually have associated value judgments. They are also used in science, sometimes presenting problems of bias; for example, "Cowbirds deposit their eggs in the nests of other species that raise the *freeloaders*," suggests how cowbirds and their young should be viewed (Flannery, 2009). Although the reader may have many associations for cowbirds and the word "freeloader," the

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mind filters out those that are not similar for the two subjects (Black, 1954). It is the flood of mental associations that helps the learner begin to make sense of the new concept and to connect it to other ideas.

As mentioned previously, metaphors are often used in poetry to convey emotions and values. Poetry has been used as a way to infuse creativity with science learning. For example, Rule, Carnicelli, and Kane (2004) used poetry-writing to motivate high school students in investigating and writing about minerals in an earth science class. An unpublished poem from the study (by the first author of this chapter) that uses similes and metaphor to set the emotional tone and provide positive value judgments about a specific mineral also incorporates accurate scientific information. Students were guided in this process and half of the participants reported improved attitudes toward science after the instructional unit. An illustrative excerpt of the poem follows.

Rose Quartz
Rose quartz is sweet like the nose on a bunny,
It's pretty and nice; sometimes even funny.
It's the colour of roses arching over a gate,
Carnations and clovers painted 'round a cake plate,
A party dress ribbon, pink lemonade punch,
Bubble gum ice cream and jellybeans for lunch,
A fist full of Easter grass, iridescently pink,
Or a powder room rug that matches the sink.
It's smooth and its round – so glass-marble cool,
Carved into statues or cabochon jewels,
Polished as beads or set into rings,
Made into boxes to cherish small things.
It's harder than window glass; difficult to scratch.
Strong Si-O bonding provides a good match.
A substance that's carve-able; yet holds its shine;
The slick, glossy feel of rose quartz is divine!
Its color's mysterious: perhaps colloidal gold,
Or manganese impurities rose quartz may hold.
Titanium could cause its colour within,
Or aligned mineral fibers of unknown origin.
Part of its charm is we don't understand,
The *pink* in that chunk of rose quartz in your hand.
Enjoy its pink radiance, pastel in hue,
Rosy perfection provides a new view.
Calming like rippling pink clouds in the sky,
Rose quartz can ease an over stressed eye.
Rest yours upon it and soon you will know,
Peaceful relaxation of rosy quartz glow.

Analogies, in contrast to metaphors, are used less for drama and more for a direct comparison between concepts to highlight the common relationships of their various features. Inferences can be drawn about the less familiar concept on the basis of what is known about the more familiar concept (Harré, 1972). Deeper understandings of complex concepts can be facilitated by abstracting the most important ideas from the system, delineating its boundaries, and providing appropriate language for presenting a scientific explanation (Arnold & Millar, 1996). Analogies are important to science learning because they often allow the learner to mentally picture a complex concept and may also help in scientific research by alerting the mind to unnoticed, possibly parallel features that may then be explored.

Analogies play several important roles in student learning (Venville & Treagust, 1996): (1) transferring the structure from an unfamiliar domain to a familiar one to aid understanding; (2) motivating students and increasing their self-efficacy in learning science content; (3) facilitating change in mindset of the learner from “matter” to “processes” and (4) supporting memory in recalling features and interactions of a concept. Further evidence of the utility of analogical thinking in memory retrieval comes from several experiments conducted by Gentner, Loewenstein, Thompson, and Forbus (2009). They found that when analogical comparisons were used during learning, later retrieval of information was improved, probably because of the mental representation of the information in abstract comparison categories. They also examined participants’ retrieval of a problem-solving strategy when analogy was used at the time of retrieval rather than at the time of learning, showing that this technique enhanced recall and application of the remembered strategy.

Gentner and others (Gentner & Lowenstein, 2002; Gentner & Medina, 1998) have suggested much of children’s learning strategies are based on similarity comparisons with analogies being particularly valuable in enabling children to abstract relational knowledge structures. Valle and Callanan (2006) showed that parents effectively used analogies to communicate new science concepts to their four to nine year old children at two science museum displays (topographic maps and a zoetrope exhibit of animation) and through explanation of science in a homework problem about infections. A post-task assessment demonstrated that children whose parents used relational analogies in their explanations performed better.

Assessments Using Analogy

Some classic gifted education creativity tests (e.g., Getzels & Jackson, 1962) asked subjects to generate as many uses for a common object (e.g., pencil, paper clip, brick) as possible, requiring the person to think of properties of the object and how the object might be used differently to exploit one of these properties analogously to another known object (e.g., a heavy brick could be used as a door stop). Similar activities are often used as thinking exercises for gifted students. Intelligence/achievement tests that focus on analogy include the well-known Miller Analogies Test (PsychCorp, 2011) that phrases all items as analogies with a final multiple choice response to complete the analogy and sections of the Graduate Record Exam (Educational Testing Service, 2012). Use of analogy in advanced testing is a testament to the higher levels of thinking addressed by this type of comparative thinking.

USE IN SCIENCE TEACHING

Metaphors in Science Teaching

Metaphors help students make sense of new experiences by connecting them to what they already know. Jakobson and Wickman (2006) examined the spontaneous metaphors and similes of elementary students as they were engaged in science lessons. They noted that children's comparisons of the natural phenomena they were observing to qualities of other things helped them focus on and remember those characteristics. Secondly, they observed that children's spontaneous comparisons were stepping stones to developing the final science concepts rather than endpoints in themselves. However, sometimes, children's metaphors restrict what they observe, resulting in scientific aspects of the phenomenon being ignored. Teachers, therefore, need to interact with students and ask questions that assist them in noticing other important aspects. Children often make comparisons to objects without stating which qualities make these objects similar to the natural phenomena they are exploring. Consequently, it is important for teachers to encourage them to elaborate on how the two are similar. Jakobson and Wickman also noted that because understandings of metaphors and similes rely on prior experiences, all comparisons will not be equally effective for all students. Additionally, some metaphors contain negative aesthetic or value judgments that hinder students from exploring the phenomena further. The researchers of this study suggested that teachers might make a game of students trying to think of positive metaphors when a conversation turns negative. Additionally, the teacher can mediate metaphors that appeal mostly to one gender or culture by suggesting more universal ones.

Teaching with Analogies

Analogies serve as early mental models that connect prior knowledge to developing understandings, but they may be used ineffectively when a learner interprets unshared attributes as valid or when learners are not familiar with the analogy (Harrison & Treagust, 1993). Therefore, teachers need to guide students in mapping the relevant features of the analogy and in identifying its limits (Adúriz-Bravo, Bonan, Galli, Chion, & Meinardi, 2005).

The Teaching with Analogies Model helps students avoid some of the problems associated with using analogies to explain complex concepts (Glynn, 2007, 2004; Glynn, Duit, & Thiele, 1995). This model has six steps: (1) introduce the new, unfamiliar concept called the *target* concept; (2) remind students to think about what they know about the *analogue* concept, a familiar concept to which the target will be compared; (3) identify the most important features of both the target and analogue concepts; (4) connect the ideas from the two concepts that have the same types of relationships through mapping – drawing a diagram or making a chart; (5) identify areas in which the comparison breaks down; and (6) draw conclusions about the target concept – what do students now understand about this new idea since comparing it to a familiar idea? For teaching through analogies to work well, both target and analogue need to have a number of similar features; the more features shared, the better the analogy.

The pairing of components from the target and analogue that have similar roles in each system is called *structural alignment* and is accomplished through mapping. Mapping can be made visible through a chart that connects the two features (one from each system or domain). Gentner and Markman (1997) identified three psychological constraints on the alignment of an analogy: (1) structural consistency, (2) relational focus, and (3) systematicity. One-to-one correspondence of features of the target and analogue with matching relationships within their respective systems constitutes structural consistency. Relational focus means that the paired elements do not have to have similar visual or surface appearances; they just need to have similar relationships in their systems. Systematicity refers to the fact that analogies are comparisons between systems of related elements.

Bridging analogies (Brown & Clement, 1989) can also be used to assist students in understanding difficult concepts. There are four steps to this process, illustrated here with a physical science case: (1) Student ideas that are inconsistent with scientific knowledge are made clear by using a target question. For instance, the teacher may ask if a table exerts a force on the book resting on its surface. A student responding, “No, because the table is not moving,” is exhibiting an idea that does not match scientific understandings. (2) The teacher suggests an analogous case that students find intuitively acceptable, such as considering a hand pressing down on a spring. This is called the *anchoring analogy*, because it forms the strongly accepted end of a chain of ideas that will connect to the disputed idea. The teacher asks, “Does the spring exert a force on the hand? (3) The teacher asks students to compare the two analogies: the book on the table and the hand on the spring. (4) The teacher supplies another analogy that is closer to the book on the table, because it is easier to understand a close analogy than a distant one. This is the *bridging analogy*. In fact, several close analogies many be provided to bridge the gap between the target case and the anchoring analogy. In this situation, the teacher may ask students to consider a book resting on a foam cushion or suspended by a flexible strip. A study of Turkish high school students using bridging analogies to study physics concepts demonstrated that both male and female students learned more compared to a control group (Yilmaz, Eryilmaz, & Geban, 2006).

Active student engagement in acting out an analogy can assist students in better understanding the science. For example, upper elementary students learned how an electric circuit works by forming a loop with a table (representing the battery) as part of the loop (Ashmann, 2009). At the end of the table designated as negative, a large pile of pennies was placed. A few pennies were also placed at the opposite, "positive" end of the table to represent the electrons present there. Each student, standing shoulder to shoulder, had one hand behind the back and one in front, grasping a single penny. The circuit operated as the student next to the positive end of the battery felt an imagined attraction of that end of the battery for her negatively-charged electron-penny and placed it on the table. This allowed her to take the penny from the person next to her and to continue the chain reaction of penny movement around the circuit. She continued to place pennies at the positive end of the battery, taking pennies one at a time from the person next to her. The person at the negative end of the battery took single pennies from that end of the table to feed the current until the pile of pennies at the negative end of the battery was exhausted and the battery was "dead." Students were also able to act out how an insulator stops current, how a light bulb operates, and the differences between series circuit and a parallel circuit.

Generative analogies are so-called because these analogies are created and modified by students as they explore a concept (Wong, 1993). Students who generate their own analogies think deeply about concepts and tend to ask important questions. Generative analogies are effective because they originate from a students' base of understanding, thereby avoiding analogies not understood by students. Students activate and connect to previous knowledge as they attempt to devise the analogy. The process of devising an analogy pushes the student to probe and question their current understandings of the topic.

Many successful science analogy lessons have been documented in the professional literature. For example, Orgill and Bodners (2007) used a two by two pane of postage stamps as an analogy for the binding of oxygen to hemoglobin. To remove the first stamp, two perforated sides must be torn, just as the binding of an initial oxygen molecule to hemoglobin requires quite a bit of energy. The second and third stamps removed requires less tearing and less energy just as binding of successive oxygen molecules requires less energy. In their study, students reported better understanding of course information, increased ability to visualize biochemical concepts, and improved recall of content. Additionally, the results of the investigation indicated instructional analogies increased student motivation and enhanced communication of science ideas.

Using analogies can help students conceptualize relationships that exist between structure and function within a complex system rather than merely memorizing information. Student-created analogies facilitate students' higher levels of thinking and actively involve them in the process (Marzano et al., 2001). Middle school learners who created models of cells as cities, restaurants, baseball games, or homes (Grady & Jeanpierre, 2011) showed increased test scores compared to previous groups who did not engage in such work, indicating their improved understanding of cell parts and functions. However, it is important to note that use of analogies in teaching a science concept may not be enough; additional opportunities to understand, discuss, and apply the new ideas are important (Guerra-Ramos, 2011).

Models

Mental representations of physical phenomena or systems that have analogous structures (similar spatial arrangement and relationships between components) are mental models (Gilbert, Boulter, & Elmer, 2000). If the relationships between the parts are causal in nature, then one can mentally "run" or conduct a simulation of the model to make predictions and explanations (Nersessian, 2008). A person's mental models of phenomena continuously evolve throughout the lifetime, changing as the individual encounters new situations. However, although a mental model may evolve to be a scientifically accepted one, individuals may fall back on past ideas or experiences to generate predictions and explanations, rather than actively engage to mentally manipulate the model they espouse as correct. Because of this potential fallback to earlier naive conceptions, it is important to provide in-depth explanations of the underlying mechanisms of how the physical processes work (Chiou & Anderson, 2009).

Physical models are another type of analogy. Beads woven together with nylon thread can be used to model many chemical structures, such as fullerenes, in which each spherical bead represents the electron density of a carbon-carbon bond (Chuang, Jin, Tsoo, Tang, Cheung, & Cuccia, 2012). The construction of models helps students notice the symmetry of the molecule in the three-dimensional representation of its configuration. Another activity described by Nassiff and Czerwinski (2012) showed how students in a high school chemistry class used large and small paperclips to model the Law of Conservation of Mass. Students took different quantities of large, then small paperclips, adding them together to be weighed. Then they linked one small to each large paperclip to form the compound LgSm (Large-Small). They weighed the product LgSm and leftover small and large paperclips, comparing it to the initial weight of the original quantities to verify the law.

PROBLEM-SOLVING AND CREATIVITY

Combination of Elements

Many eminent scientists have also been artists such as Leonardo da Vinci and Richard Feynman. Root-Bernstein (2003, p. 267) states that ".many scientists and engineers employ the arts as scientific tools and that various artistic insights have actually preceded and made possible subsequent scientific discoveries and their practical applications." He outlined four ways that the arts assist scientists: (1) new phenomena are often invented or discovered by the arts before being investigated by science; (2) the arts supply non-traditional physical and mental tools including models and analogies for problem-solving; (3) words, images, and models used to communicate scientific ideas and results often come from the arts; and (4) fantasy and the generation of possible worlds for exploration and testing according to real-world constraints contribute to scientific discovery and invention. Perrine and Brodersen (2005) found that both artists and scientists share the personality trait of openness to experience, but in artists this is best seen as openness to aesthetics, while in scientists it is openness to ideas.

Michalko (1998) postulated that successful ideas of creative geniuses come from having a rich pool of alternatives and conjectures from which to choose the best, likening it to the blind mutation pool in biological evolution from which only the best adapted changes survive. He studied eminent scientists, inventors, and artists, compiling their creative thinking strategies for generating ideas, summarizing them into two categories: (1) ways to see what no one else is seeing, and (2) ways to think what no one else is thinking. The first category addresses perception, including defining the problem at different levels of scope or perspective, attending to different aspects of the issue, and making thoughts visible through a large variety of diagrams. The second category focuses on ways to generate "blind" ideas that are shaped by chance or random factors. A strategy that supports this category is determining major parameters of a challenge and listing possibilities for each. Then the possible solutions are created by randomly selecting one possibility for each parameter to create a whole that combines different elements. According to Michalko, Leonardo da Vinci used this technique in drawing a large variety of grotesque heads or caricatures by making a chart of major features of the head (overall shape, eyes, nose, mouth, chin) and listing possibilities for each (e.g., for the chin: double-chinned, slack-jawed, sagging, angular, receding, projecting). After providing several techniques for combining and connecting ideas, Michalko suggested, among other strategies, that one can use similarities, differences, and analogy between domains to produce new ideas.

Thagard (2010) evaluated the *combinatorial conjecture* that all creativity results from combinations of mental representations. He studied two existing lists to avoid any personal bias, not arguing whether the selected one hundred were actually the ultimate "best", but assuming that they all were, indeed, important: (1) one hundred important scientific discoveries (Haven, 2007) and (2) one hundred great technological inventions (Philbin, 2003). He concluded from his analysis that all of the hundred scientific discoveries show evidence of combination of concepts leading to the discovery. New concepts (evidenced by newly–coined words) occurred in only 60 of the 100 cases, while analogy was used in 14 discoveries, with all but two of these involving comparisons across different domains. Forty-one of these involved visual representations while 87 of the 100 technological inventions used visual representation. Twelve of the inventions used analogy with seven of these being across domains.

Analogies in Problem-Solving and Innovation

"[A] problem occurs when there is an obstacle between a present state and a goal and it is not obvious how to get around the obstacle" (Goldstein 2005 p. 388). Problems can be well-defined or ill-defined (Kahney, 1994). A well-defined problem provides the solver with all the information necessary to solve the problem. This information falls into these four categories: the initial state, the goal state, legal operations, and operator restrictions. An ill-defined problem is missing one or more of these types of information. Analogies can be useful in solving problems if the solver recognizes the similarities between two analogous problems and can also recall the solution to the problem (Condell, Wade, Galway, McBride, Gormley, Brennan, & Somasundram, 2010). Comparing two similar problems helps people develop a general schema that operates across domains, making them more able to think of the problem in broad terms and use analogous thinking to solve it. However, functional fixedness, the inability to perceive new relationships or uses for objects, and mechanization of thought (using the same problem-solving steps for all problems) inhibits the problem-solving process (Anderson, 2005); therefore, it is important for problem-solvers to recall possible applicable methods while remaining open to new approaches.

Visual analogies (analogical reasoning with visual knowledge) are important in architecture (Casakin, 2004) and other types of design (Ferguson, 1992). Davies, Goel, and Nersessian, (2009) analyzed the sequence of drawings made by undergraduate college students who were presented with the problem of designing a weed trimmer that extends on a pole from a truck to trim the roadside but needs to be able to "pass through" traffic signposts. A diagram and a description of an airlock vestibule separating a clean room from the rest of the building were provided for students to use as an analogy in solving the problem. Davies and colleagues determined how the new designs for the weed trimmer may have been produced by incremental transfer from the provided airlock example and developed a computer program that simulated the visual input and output of several of the participants. They concluded that designers can create new solutions by transferring ideas from prior, analogous models by using visuospatial representations of the stages of the design organized in chronological order. Their computer modeling work indicates that analogical transfer can occur using only visuospatial knowledge. This reinforces the importance of using visuals such as diagrams in creative thinking, as previously discussed when mentioning Michalko's creative thinking strategies.

The use of analogy assists scientists in making structured connections between different domains to better understand how they work and to exploit well-known relationships in one domain for innovations in another. Many scientists and inventors have used analogy to assist them in making conceptual breakthroughs. For example, James Dyson, while looking for ways to make vacuum cleaners more effective, observed the whirling action of a sawmill cyclone sucking sawdust without becoming clogged. His first vacuum cleaner prototype was based on this analogy (Foreman & Drummond, 2008). Similarly, Hans Krebs defined the citric acid cycle, later named the Krebs Cycle, by recognizing the similarities of parts of the chain to components in other cyclic processes (Lightman, 2005). Likewise, Charles Darwin compared evolution to a tree, connecting budding twigs to existing species and older growth as the long succession of extinct organisms. He noticed that new growth overtops older branches, blocking the light from them in the same way that new species may outcompete others in the struggle for resources. This analogy helped Darwin notice other aspects of evolution to investigate (Darwin, 1859; Marcelos & Nagem, 2012).

Analogies have been used by scientists and engineers to develop new theories and experimental approaches. For example, in the area of artificial intelligence, Brooks (1999) used an analogy to convince many members of his field that concentrating on general aspects of intelligence such as vision and movement were more important to the development of artificial intelligence than the then-current approach of focusing on specialized intelligence like solving difficult mathematics or playing chess. The analogy he employed in this argument was that nature required over three billion years for life to evolve from single cells to insects, but only 450 million years to evolve from insects to humans. The conclusion to be drawn is that basic properties of life are more difficult engineering problems and should form the foundation for artificial intelligence in a bottom-up manner, rather than trying to reproduce more specialized aspects first (a top-down approach) (Gibson, 2008).

Experts Compared to Novices

It has been posited that it takes about ten thousand hours of concentrated effort to reach expert level in most academic fields, sports, and games (Ericsson, 1996). This information is important to educators of gifted and talented students, as it indicates that preparation in a student's area of interest should begin early.

"An expert is a person with special knowledge or ability to perform an allocated task skilfully," whereas a "novice is someone who is new to the field or activity" (Condell et al., 2010, p. 232). Several studies have delineated the differences between the ways experts and novices solve problems. Experts work backward from the unknown to the given information in a "means-end" approach, while novices write down the given information and try to make connections to the unknown (Larkin, McDermott, Simon, & Simon, 1980). Experts search a greater breadth of possibilities than novices and consider the consequences of each step (deGroot, 1965). They are able to recognize crucial configurations of information and their implications. Experts in physics arrange their knowledge in a hierarchical fashion, producing specific solutions to the problem; whereas novices are less organized and more general in their solutions (Larkin et al., 1980). Physics experts also used underlying science concepts rather than surface features and use multiple representations of the problem.

Schenk, Vitalari, and Davis (1998) identified five differences between experts and novices: (1) novices have less knowledge about the domain, which limits their ability to ask important questions to gather information and therefore generate good solutions; (2) Experts tend to involve users in the system development stage; (3) Experts react to specific information rather than general triggers; (4) Experts generate more hypotheses and goals for the problem; (5) Experts notice features and patterns differently than novices.

Easton and Ormerod (2001) found that both experts and novices spend the same amount of time working on a problem, but experts provide more alternative recommendations, critical issues, evaluation criteria, and more quantitative rather than qualitative solutions. Experts are able to activate and retrieve previous knowledge related to the problem but may take more time in solving the problem because they spend more time understanding it (Hung, 2003). Experts, however, only outperform novices when solving problems in their area of expertise. Otherwise, they perform similar to novices because their advantages are based on their store of previous experience and knowledge in the field (Goldstein, 2005).

Experts are more likely than novices to recognize analogical relationships between different situations and to encode these into memory, allowing later retrieval (Blanchette & Dunbar, 2001). Memory retrieval of this type of relational information is very important to effective problem-solving and functioning in many educational and workplace situations (Pfeffer & Sutton, 2000). The most effective means of relational transfer is for the person to compare analogous examples during learning (Gentner, Loewenstein, & Thompson, 2003).

Form and Function Analogies

Form and function is a unifying concept of science noted in the National Science Education Standards (National Committee on Science Education Standards and Assessment and National Research Council, 1996) that can be applied to both the natural and designed world, therefore allowing analogies between these domains. *Forms*, physical properties that include shape, colour, pattern, texture, motion, and configuration, support the *functions* of manufactured objects or natural organisms such as animal body parts and plant parts. Research studies have shown the efficacy of high school students using form and function analogies to learn human body systems (Rule & Furletti, 2004), and of second graders learning animal adaptations (Rule, Baldwin, & Schell, 2008).

The two studies just mentioned utilized a unique instructional material called an “object box,” which was a set of small manufactured items (the “objects”), each representing an analogue, and a set of corresponding two-sided cards housed in a plastic shoebox (the “box”). The front of each card described the form and function of an animal body part (second grade study on animal adaptations) or a component of a human body system (high school study). The student’s first task was to take a card, read about the form and function, and then search through the objects to locate one that had a similar form and function. This activity had the advantage of being hands-on and of having concrete examples of the analogues used in the analogies for students to examine. The reverse side of each card presented the name of the correct analogous object and an explanation of how its form and function matched that of the target. Figure 1 shows example card fronts and backs from a form and function analogy object box about the saguaro cactus. Although not used in either of the mentioned studies, this example shows the form and function relationships well and was similar to the sets used in the study. The fronts of the cards are shown on the left and the backs of the cards (with the corresponding answers) are shown on the right.

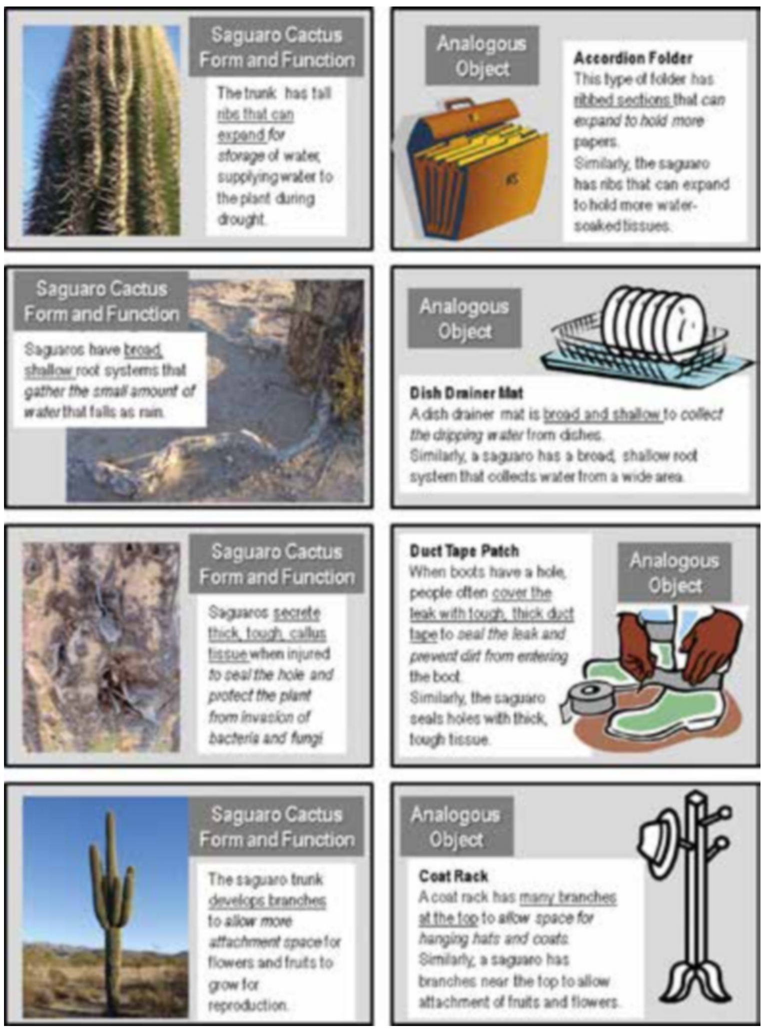

Figure 1. Example form and function analogy cards for the Saguaro cactus

A sequence of activities to enhance learning through deeper analysis of the analogies was used in both studies. First, students matched the cards to objects as just described. Next, students chose one of the objects and mapped the relationships between the target and the analogous object, using a chart like the example in Table 1 that maps the analogies between a saguaro cactus and an accordion folder. The limits of the analogy were noted on the bottom of the chart.

Table 1. Mapping of the analogy of a saguaro cactus and an accordion folder

Saguaro Cactus	*Similarities*	*Accordion Folder*
Saguaro ribs	Both are expandable	Accordion-like sections
Widens to store water	Widens when fuller	Widens to store paper
Stores water	Storage mechanism	Stores papers
Contracts during drought	Can contract	Contracts when few papers
Waxy skin to seal out organisms	Protective skin	Tough paper and clasp to protect documents
Saguaro Cactus	Limits	Accordion Folder
Living plant	Different materials	Thick paper
Green	Different colouration	Brown or variety of colours
Naturally growing	Different origin	Manufactured item
Stores water	Stores different items	Stores paper
In desert areas	Different location	Found in offices

Third, students considered other objects that might be used as alternative analogues for the target animal body part or human body system component. These objects needed to have the same form and function relationships as the target concept. For example, other items that could be used as analogies to the expanding nature of the cactus are: an elastic waistband, a knitted hat, blacksmith bellows, a pleated skirt, certain pleated vacuum cleaner bags, and some suitcases that can expand by unzipping a section. In the final activity, students were given a new animal body part or human body system component written on an index card. Students generated their own form and function analogy, drawing a sketch of the analogue object function on another index card. These were then mixed and students worked to match these new analogies devised by classmates, discussing issues and strengths of that work.

Form and function analogies have been combined successfully with the SCAMPER method to create new inventions or innovations of manufactured items (Rule, Baldwin, & Schell, 2009). This creative thinking technique's name, SCAMPER (Eberle, 1972), is an acronym for various operations that can produce changes for innovations: Substitute, Combine, Adapt, Modify-Minify-Maximize, Put-to-another-use, Eliminate, and Rearrange. These ideas were developed from

Osborne's checklist (1963) of tactics for producing creative transformations. First an item is identified to which innovation or invention will be applied. In work with second graders, Rule et al. (2009) used simple items such as an envelope, plastic spoon or paper cup. A chart is used to implement this technique, as shown in Table 2. The first column has the creative SCAMPER operations that will be applied to ideas; the second column is used to note a form and function relationship present in one or more organisms that will be applied to the item in conjunction with the SCAMPER operation to generate ideas for innovation. The combination of disparate ideas in this manner is called forced relationships, an effective strategy for producing novel ideas (Guilford, 1986). The last column shows ideas for innovation of the product, in this case, a canvas tennis shoe.

Table 2. Applying the SCAMPER technique in conjunction with form and function to generate ideas for improving canvas tennis shoes

SCAMPER Operation	*Saguaro Form and Function Idea*	*Idea for Improving Tennis Shoe*
Substitute	Saguaros have broad shallow root systems	Substitute broad woven mats for soles to walk easily on sand.
Combine	Saguaros have branches to support colourful flowers and fruits	Attach flowers and baubles to the shoestrings to make them more attractive.
Adapt	Saguaros have a waxy skin to prevent water loss and keep out pathogens.	Sell a waterproofing gel that can be applied for walking in wet grass or puddles.
Modify, Minimize, Maximize	Saguaros have ribs so they can expand.	Have pleated fabric along the side so that a swollen or growing foot is easily accommodated.
Put to Another Use	Saguaros have spines to protect them from browsing animals.	Fill old shoes with cement and use as a self defence weapon.
Eliminate	Saguaros develop tough tissue to seal wounds.	Have a tube of gel that can be applied to worn spots in the canvas to seal and eliminate them.
Rearrange	Saguaros have wooden rings inside to support the trunk and branches.	Take the insole out and use it as padding for the ankle with a higher, more supportive shoe top.

USING ANALOGY IN PREPARING GIFTED INDIVIDUALS

Use of Analogies in Gifted Education Programs

Many problem-solving activities for gifted students require students to reuse or re-purpose common items such as plastic lids, cardboard trays, plastic bottles, and Popsicle sticks to make a project. For example, the Future City problem-based program with computer simulation (Gardiner, 2007; National Engineers Week Future City® Competition, 2011) requires students to design a model of their planned city with recycled materials after using simulation software to design their city. Another problem-solving exercise using analogical thinking for gifted students is one described by Rule et al. (2011; 2012). In this activity, participants are each given an identical set of recycled and craft items, given a theme, and asked to make a scene or object related to the theme in a limited amount of time. Participants must envision the various recycled items as new analogous parts of the construction.

Synectics, a Greek word meaning binding together of seemingly unrelated elements, was the term used by Gordon (1961) for his program of strategies aimed at uncovering the psychological mechanisms for creative activity. He first developed these skills for use in industry while he was a member of a consulting group that helped businesses develop new product ideas, but later they were applied to developing workbooks for gifted education (Gordon, 1974). The synectics program utilized analogical thinking strategies (among other strategies) including personal analogy and direct analogy. In *personal analogy,* the participant puts himself or herself in the place of one of the objects involved in the problem to be solved – *becoming* the object. How the object is feeling, moving, wishing, and interacting with other objects is verbalized using imagination, emotions, and the senses. *Direct analogy* uses animals, appliances, everyday items, or systems to make analogies to the problem or parts of it to enhance idea production for a solution.

Synectics also offered an additional strategy for problem-solving. First, everyone is reminded to postpone judgment of ideas. A facilitator asks the participant to state the problem. Group members translate the problem into wish form, "I wish that." and the participant chooses a few that seem to represent the problem best. The participant explains what words or phrases made the chosen wishes most appealing. The facilitator leads the class in imagining an excursion to a distant place, describing the scenes and events encountered there for a few minutes and making connections to the favoured words and phrases. Then, class members use that excursion to form connections and analogies to the problem at hand, often generating unusual perspectives that assist in finding a solution. For example, a second grade student may choose this statement: "I wish I could make a book of shadows that presents mysteries." The facilitator may take the class on an imagined cave tour with many formations that are likened to common objects when viewed from different perspectives and which reveals mysterious cave inhabitants such as blind fish and crickets. The class may connect mysteries in the cave darkness to guessing the object that made a shadow and viewing objects from different perspectives to matching different shadows of the same object created by moving the light source.

Another successful approach for school-wide enrichment and gifted programming is the Talents Unlimited Thinking Skills Program (Schlichter & Palmer, 1993), which provides a set of thinking skills to be used in kindergarten through high school education. This system consists of the following talents (to be combined with specific academic talent such as science): productive thinking, planning, decision-making, forecasting causes and effects, and six additional communication talents. One of the communication talents is generating similes using the words "like" or "as" and adding details to portray the situation in which the similarity is at its most magnified point. For example instead of saying, "The butterfly was as colourful as a painting," the simile would be taken to the limit by saying, "The butterfly was as colourful as a bold Mondrian painting of black, white, and primary colours."

CHAPTER SUMMARY

Comparative thinking is a fundamental cognitive process that positively affects student learning. Metaphors, similes, and analogies use mental associations that assist the learner in making sense of new concepts and in connecting them to existing knowledge. Poetry containing metaphors mixed with science information can infuse creativity with science while conveying emotions and values that motivate students. Analogies allow learners to draw inferences about a less familiar concept through what is known about the more familiar one, thereby aiding understanding, self-efficacy, and memory along with moving the learner to focus on process. Gifted education creativity tests often assess quantity and quality of idea generation through analogy tasks while college entrance or achievement tests use analogy to assess vocabulary and fine divisions of concept understanding.

Analogies are useful in science teaching and learning. Children often make spontaneous analogies when discussing observations of natural phenomena; discussions with adults can facilitate, enrich, and guide their use of analogies. Effective analogies make reference to familiar analogues and clearly define the limits of the comparison. Mapping the paired components from the new target idea to the familiar analogy, a process called structural alignment, helps in this process. A series of analogies can assist students in understanding difficult concepts by starting with one easily understood and then moving to others that are closer to the unfamiliar concept, bridging analogies. Kinesthetically dramatizing an abstract science process through analogy with concrete objects or actions facilitates student understanding. Asking students to generate and demonstrate analogies of science processes is effective because learners must think deeply about the concepts, often asking important questions, while operating from the learner's base of understanding. Many teachers successfully use analogy or physical models made with common items such as beads and paper clips to present difficult science concepts to students.

Creative scientists have used arts ideas such as exploration of imagined worlds and use of words, images and models derived from the arts to fuel their ingenuity. Eminent scientists, inventors, and artists examined problems from different perspectives and tried many combinations of ideas. Analogies can be helpful in problem-solving by allowing the individual to apply a previous solution to a problem in another domain to the present problem. Drawing sketches of problem steps can assist in translating and applying this knowledge. Many scientists have had breakthrough ideas that resulted from analogies to other domains. Experts differ from novices regarding solving problems in the domain of their expertise. They search a greater breadth of possibilities, generating a hierarchical set of problem solutions with critiques. They are more likely to recognize and use analogical relationships. Form and function analogies are useful for comparing natural to manufactured objects and systems and have resulted in many innovations. Hands-on sets of materials that include objects and analogy explanations on cards, along with analogy mapping and generation activities can assist students in deeper understanding of concepts such as human body systems or animal adaptations. Combining these ideas through creative operations such as substitute, combine, or adapt and applying them to a given objects can produce innovative ideas.

Analogy has been used in gifted education programs in many ways. Re-purposing of materials to design models, scenes, or objects provides hands-on, engrossing activities. The Synectics program utilized personal analogies of becoming the object, direct analogies, and fantasy analogical excursions to develop solutions to problems. Another popular thinking skill program encouraged students to develop similes that used descriptive phrases that magnified the comparison being made, thereby communicating the idea well. The wealth of applications of analogy to idea generation and science understanding make this approach an essential component of science and gifted education.

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