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THE IMPORTANCE OF EXPLICITLY MAPPING INSTRUCTIONAL ANALOGIES IN SCIENCE EDUCATION

by

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A dissertation submitted in partial fulfillment
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ABSTRACT

The Importance of Explicitly Mapping Instructional Analogies in Science Education

by

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Analogies are ubiquitous during instruction in science classrooms, yet research about the effectiveness of using analogies has produced mixed results. An aspect seldom studied is a model of instruction when using analogies. The few existing models for instruction with analogies have not often been examined quantitatively. The Teaching With Analogies (TWA) model (Glynn, 1991) is one of the models frequently cited in the variety of research about analogies. The TWA model outlines steps for instruction, including the step of explicitly mapping the features of the source to the target. An experimental study was conducted to examine the effects of explicitly mapping the features of the source and target in an analogy during computer-based instruction about electrical circuits. Explicit mapping was compared to no mapping and to a control with no analogy.

Participants were ninth- and tenth-grade biology students who were each randomly assigned to one of three conditions (no analogy module, analogy module, or

explicitly mapped analogy module) for computer-based instruction. Subjects took a pre-test before the instruction, which was used to assign them to a level of previous knowledge about electrical circuits for analysis of any differential effects. After the instruction modules, students took a post-test about electrical circuits. Two weeks later, they took a delayed post-test.

No advantage was found for explicitly mapping the analogy. Learning patterns were the same, regardless of the type of instruction. Those who knew the least about electrical circuits, based on the pre-test, made the most gains. After the two-week delay, this group maintained the largest amount of their gain.

Implications exist for science education classrooms, as analogy use should be based on research about effective practices. Further studies are suggested to foster the building of research-based models for classroom instruction with analogies.

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I truly appreciate the assistance of the teachers who participated in this study. They collected permission slips and gave up some class time in order to have their students participate. Although they must remain unnamed, I appreciate the 9th- and 10th-graders who served as subjects.

This accomplishment would not have been possible without the support of my patient husband, Don R. Asay, my children, and my grandchildren. My family, at the right times, listened to me, pushed me, encouraged me, and challenged my priorities. It may seem strange to express gratitude for the support of my young grandchildren. However, many years ago, the growth and development of my own children instilled an incredible curiosity about learning in me. Through grandparenting the next generation, this desire has only grown. I am constantly humbled and in awe as I watch them learn and grow. I sincerely hope and pray that I will never lose that appreciation for learning, a process of growth that can stretch through the eternities.

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CHAPTER 1

INTRODUCTION

Children carry treasure boxes of knowledge and experiences to their science classrooms. The challenge for teachers is to find ways to use that treasure. Used strategically, analogies can unlock that knowledge and put it to work developing or refining scientific understanding of phenomena. Analogies are ubiquitous in the world of science education and have been the focus of much research over the last 30 years. Models of analogy use have been proposed, developmental aspects have been studied, analogies in textbooks have been analyzed, computer models have been built, and research on the cognitive processes involved has been done. After all of this research, the efficacy of analogies is still questioned, as mixed results have been found.

Analogies provide a way to link and organize new information based on previous knowledge. From what we know of the processes of learning, these tools should be useful for learning. Therefore, strategies for analogy use should be based on both learning theory and evidence of effect. The purpose of this study was to quantitatively examine the effectiveness of a classroom model of analogy use, specifically the step of explicitly mapping the components of the source and target for instruction about electrical circuits.

Analogies

Description of Analogies

The term “analogy” is used to describe a variety of phenomena. In general, analogies are mechanisms for showing the relational structure between two systems, domains, or concepts, with varying degrees of similarity among features. Analogical reasoning is a process of aligning similarities between different ideas or systems so that

information is transferred from one system to another (Duit, 1991; Gentner, Bowdle, Wolff, & Boronat, 2001; Gentner & Markman, 1997; Holyoak, 2005).

Analogies are conceptual models in which a familiar source provides information that is transferred to a less familiar or unknown target, a process of inductive reasoning. The useful similarity between the source and target is based on the relationships or structures, rather than on surface features. For example, when the solar system is used to understand an atom, few of the physical features are the same. However, the relationships between planets and the Sun allow inferences to be made about the relationships among subatomic particles.

Analogies are models (Newton & Newton, 1995), and, as with all models, are limited as to the similarities between the source and target. If the match were exact, after all, the target would simply be an instance or example of the source phenomenon. At some point, therefore, all analogies break down. Inferences can be made about the target, based on the similar, but not exactly the same, relationships in the source. In the example used above, neither the features of or relationships among the components of our Solar System are the same as those among subatomic particles.

Analogies are not metaphors, instances, or descriptions of phenomena. Metaphors compare implicitly and figuratively as information from one concept is mapped to another. Analogies explicitly map relationships, rather than physical features, from one concept to another. Analogies have an element of comparison, and are not examples or instances, which share **both** features and relationships (Gentner & Markman, 1997). Likewise, descriptions of phenomena are not comparisons; therefore, they are not

analogies. The distinction is that an analogy can be used to describe a phenomenon by transferring a familiar description to a target (Markman & Gentner, 2000).

Analogies are used in a variety of ways. People seem to naturally use analogies for explaining and clarifying (Dagher, 1995; Krawcyk, Holyoak, & Hummel, 2005). Often analogies, especially in science education, help make an abstract concept or principle more concretely understandable (Paris & Glynn, 2004; Treagust, 2007). Teachers often use analogies to promote conceptual understanding or conceptual change (Brown & Clement, 1989; May, Hammer, & Roy, 2006). In problem solving, a solution can be mapped onto an analogous problem (Clement, 1998; Gick & Holyoak, 1983; Holyoak, 2005; Yanowitz, 2001). Hypotheses and theories have been generated on the basis of analogies, often in a pathway from one analogy to another, as understanding develops (May et al., 2006; Minstrell, 1982; Tohill & Holyoak, 2000). Finally, analogies are used to access culturally identifiable information (Valle & Callanan, 2006), such as proverbs about culturally valuable characteristics or cautionary tales for children.

Types of Analogies

With all of the ways analogies are used, it became obvious to me that the term is used to describe many variations of a phenomenon. To organize and focus my research, I identified four kinds of analogies: 1) Naturalistic analogies are sociocultural in nature. Some have become so embedded in our language that they call up mental images, shared experiences, or even technical knowledge. 2) Reading analogies tap into the rimes used when learning to read. Children can use the component phonemes, with which they are familiar, to read new word. 3) Classical analogies have a specific form to indicate the similar relationships in pairs. Usually this is noted as A:B::C:D, in which A is related to

B in the same way that C is related to D. In classical analogies, both pairs are usually familiar, a fundamental difference between classical and instructional analogies. 4) Instructional analogies promote learning; they use a transfer of information about a base or source to a target concept, capitalizing on existing knowledge to promote learning or understanding about something new. The fourth type of analogy is the focus of my research.

Instructional analogies are especially important for science education. A great deal of science education focuses on helping students relinquish their naïve or naturalistic explanations in order to understand and accept scientifically sound explanations (Driver, Leach, Millar, & Scott, 1996; Vosniadou, 1989). Treagust (2007) suggests that so much of conceptual understanding that leads to scientific reasoning is about abstract, invisible, or symbolic information that analogies are needed to connect everyday experiences to scientific understanding.

How Analogies Work

Cognitivism provides the theoretical basis for understanding analogies. Humans store information in organized networks of schema. When faced with new information, existing schema or chunks of knowledge are activated, and the new information is processed in working memory, gaining meaning from the activated schema. The new and the revised schema are connected to the old in networks in long-term memory (Anderson & Matessa, 1997; Anderson & Pearson, 1984; Bruning, Schraw, Norby, & Ronning, 2004; Driscoll, 1994; Nussbaum, 2008; Reynolds, 2006).

In an analogy, the existing knowledge about the structural relationships in a source or base phenomenon, concept, principle, or system is mapped to the structural

relationships in a target (Gentner & Markman, 1997). If the source and target are aligned, a transfer of knowledge can be made to the target. Using analogies involves several processes. First, an appropriate source must be retrieved, accessed, or provided. Next, the information must be mapped to the target. Third, the mapping is evaluated for match and appropriateness, and finally, inferences about the target are made through the transfer from the source. In the best situations, the new information is organized with the old for ease of future retrieval.

These processes cannot be understood without considering what we know about memory. Working memory is where information processing takes place, including the retrieval of information from long-term memory and the mapping process in analogical reasoning. These processes tax the limits of working memory. The processes of chunking and connecting information in schema networks influence how accurately the information is stored and how it can be retrieved from long-term memory (Bolles, 1988; Bruning et al., 2004; Driscoll, 1994). Strategies, such as elaboration, which make efficient use of working memory capacity, are critical for learning new information.

Developmental Aspects

A great deal of research has probed the developmental aspects of analogical reasoning. Causal knowledge, an aspect of being able to make inferences, develops in infancy. Analogical reasoning, in general, like other types of critical thinking, improves with maturation. Children cannot understand analogies unless they can understand relationships. Piaget's work, describing analogical reasoning as out of the reach of young children, influenced much of the research (Flavell, Miller, & Miller, 2002; Goswami, 1991). However, more recently, evidence has been found that very young children are

able to generate and use analogies, especially if they are familiar with the source and target, if they can choose answers rather than generate them, and if they work with single relationships, rather than multiple (Goswami, 2001).

Instruction with Analogies

Most of the previous research about analogies in education focuses on problem solving, and little empirical work has been done with using analogies to promote learning. The use of analogies for instruction falls clearly in the guided instruction camp as a scaffold for learning (Pea, 2004). Purposeful selection of analogies for instruction requires consideration of the source and support for the transfer of information from the source to the target. The source used should be familiar to students, and a teacher cannot assume that all students have the same mental image of the source. It may be necessary to help students build the appropriate background knowledge of a source before using it. Then, students may need help understanding the process of transferring information from the source to the target. All of these teacher actions are components of guided instruction.

Studies on Instruction with Analogies

Overwhelmingly, the research on instructional analogies has been descriptive in nature. Teacher planning, student experiences, and classroom use have been studied qualitatively. (For representative examples see Brown & Clement, 1989; Dagher, 1995; Paatz, Ryder, Schwedes, & Scott, 2004; Thiele & Treagust, 1994; Treagust, Harrison, Venville, & Dagher, 1996.) Studies have also been done about the effects of multimedia and visual scaffolds for text-based analogies (Yanowitz, 2001; Zheng, Yang, Garcia, & McCadden, 2008), bridging or linked analogies (Brown & Clement, 1989; Clement, 1993; Clement & Steinberg, 2002), and analogies used in textbooks (Curtis & Reigeluth,

1984; Glynn, Britton, Semrud-Clikeman, & Muth, 1989; Orgill & Bodner, 2006; Thiele & Treagust, 1994; Thiele, Venville, & Treagust, 1995; Venville & Treagust, 1997).

Most aspects and mechanisms of analogy use have been studied. These studies have provided evidence of the structural mapping of attributes and of mapping constraints, such as one-to-one comparisons (Holyoak & Thagard, 1989; Kurtz, Miao, & Gentner, 2001; Mason, 2004). Studies of working memory constraints and the essential component of elaboration have also provided evidence that the analogical reasoning process is complex and taxing (Tohill & Holyoak, 2000). This research has provided evidence that, in order for analogies to be effective, students must understand the source or base and be able to accurately map.

Previous research has shown a variety of results using analogies as instructional tools. Treagust, Harrison, Venville, and Dagher (1996) found that high school students taught with text-based analogies used the taught concepts in fruitful ways and found the concepts more plausible than did students taught without analogies, although both groups scored statistically the same on a post-test of knowledge. With younger children, Newton and Newton (1995) and Flick (1991) found that those taught with analogies were better able to explain the new concepts. Yanowitz (2001) found no significant difference in recall between an analogy-using group and a control group. However, students in the analogy group answered more inferential questions correctly than the control group students. Zheng et al. (2008) found that multimedia analogy presentation, which they theorized would active a more complex network of prior knowledge and would involve more senses, led to both better recall and more complex understanding. The largest effect was in the interaction between multimedia and analogy. Duit, Roth, Komorek, and

Wilbers (2001) are often cited for their mixed results for analogy use. They found that students needed assistance in using analogies. Students often focused on surface features and transferred incorrect inferences or even misconceptions. In short, the same analogy helped some students and was very misleading for others.

Classroom Models of Analogy Use for Instruction

Few classroom models of analogy use for instruction are available to teachers. Many suggestions are described for science teachers about analogies to use, mostly in trade publications (see, for example, Orgill & Thomas, 2007). However, not many overarching models provide guidance on **how** to use analogies with students during instruction. The General Model of Analogy Teaching or GMAT (Zeitoun, 1984) focused on what teachers could do to use analogies in the classroom. One of the steps was to guide students. A second model is the Teaching with Analogies or TWA model (Glynn, 1991; Glynn et al., 1989). This model provides principles for evaluating instructional analogies and steps for using analogies, but was based on analysis of analogies in science textbooks, rather than pedagogical principles or research about effectiveness. A third model, the Focus, Action, Reflect or FAR model of teaching grew out of Australian teachers' use of the TWA model (Treagust, Harrison, & Venville, 1998). This model includes planning the analogy use and an evaluation of the process, but, once again, focuses on what teachers do to prepare. The use of bridging analogies, or a series of analogies (Clement, 1998) could also be considered a classroom model. This model requires a series of analogies that help a student accept and understand scientific principles. It does not address steps students use with analogies and could actually be used with any of the four models.

Need for Present Study

Classroom instructional practices could be better informed by educational research (Stanovich & Stanovich, 2003). With all of the previous research on using analogies in classrooms, however, the question to ask becomes why analogy use sometimes works and sometimes makes little difference in improving science understanding. Studies that required students to specifically use strategies related to analogy use provide evidence that strategic use can support deeper learning. Children taught to find relationships or those required to compare the source and target have learned best using analogies for science concepts (Blake, 2004; Brown, 1989; Goswami, 2001). The learned strategies persisted over time, as did the learning associated with them.

Kurtz et al. (2001) found that structured joint interpretation of the source and target by forming explicit correspondences helped university students understand concepts. Klein, Piacente-Cimini, and Williams (2007) found that requiring undergraduate students in a problem-solving task to write about the mapping was related to better explanations of the concepts. Gentner, Loewenstein, and Thompson (2003) found that students were better able to identify the underlying principle and transfer it to a different scenario if they were required to map and align two cases or examples. Comparing was related to better schemata for knowledge, related to transfer to the target, related to identifying the underlying principle, and required effort and guidance. Brown (1989) and her colleagues found that even very young children were able to use analogies for learning if the researcher suggested a strategy of remembering the source. I cite these

examples as evidence that strategies or explicit instructions for appropriately using the mechanisms of an analogy can make a difference.

Few of the existing classroom models have been quantitatively tested; most research has been qualitative and descriptive. The classroom models of analogy use proposed in the literature have no theoretical basis and have not been aligned with other educational research findings. There is a need for theoretically based research on how analogies could be used effectively. It is therefore important to the field of science education that evidence be gathered about the efficacy of the classroom models and their components.

One of the critical features of analogical reasoning is the mapping process. Features of the source and target must be aligned so that objects and predicates from one are matched to objects and predicates of the other. The inferences that are taken from the source help the learner develop and organize knowledge about the target (Gentner & Kurtz, 2006; Holyoak, 2005; Richland, Holyoak, & Stigler, 2004). I suggest that students need to be able to map in order to transfer inferences from the source to the target. A classroom model of analogy use needs to provide for this mapping process.

The Teaching With Analogies (TWA) model proposed by Glynn (1991) includes six operations or strategies. These six steps, however, were determined through analysis of textbooks and have not been tested quantitatively. One of the central operations of this model is the mapping process. Research has shown that features of the source and target must be aligned so that features and predicates from one are matched to features and predicates of the other. The inferences that are taken from the source help the learner develop knowledge about the target (Gentner & Kurtz, 2006; Holyoak, 2005; Richland et

al., 2004). However, the question remains whether the features of the source and target must be explicitly mapped or if this step can be eliminated or treated casually in the classroom.

Purpose of Study

The purpose of this study was to investigate whether explicitly mapping the features of the analogy source and target, a component of the TWA model, helps students learn and retain understanding of a science concept. Three research questions guided the study: (a) Does explicit mapping of the source and target promote more learning than using an analogy without explicit mapping? (b) Do more-knowledgeable and less-knowledgeable learners benefit differentially from mapping? and (c) Are there any benefits over time related to either of the first two questions? I hypothesized that explicit mapping of the source and target would lead to more learning than using an analogy without explicit mapping. I proposed that this would provide extra scaffolding will provide differentiation and be more pronounced for learners who previously knew little about the topic. I hypothesized that both of these effects would persist over time.

Overview of the Study

Methods

High school students (N = 436), ages 14 and 15, in biology classes were randomly assigned to receive computer-based instruction about electrical circuits without an analogy, instruction about electrical circuits with an unmapped analogy, or computer-based instruction about electrical circuits with an explicitly mapped analogy. Students were classified as Level 1 (lowest), Level 2, or Level 3 (highest) based on their previous knowledge of electrical circuits as measured on a pre-test. Pre-test, post-test, and delayed

post-test scores on a test about electrical circuits were used to gauge learning and persistence of learning. The repeated measures 3 X 3 X 3 factorial design allowed for analysis of effects and interactions among previous science knowledge level, type of analogy instruction, and time.

The decision to use the concept of electrical circuits was based on the Nevada State Science Standard P.12.C.6: “Students know electrical circuits provide a means of transferring electrical energy to produce heat, light, sound, and chemical changes” and its performance indicators for meeting the standard: “Demonstrate the use of an electrical circuit.” The exceeding standard indicator for eighth-grade is: “Describe the generation and conduction of electricity.” (Nevada Department of Education, n.d.).

Three different forms of a 20-question multiple-choice test on electrical circuits were used for the pre-test, post-test and delayed post-test. Three 20-minute computer-based instruction modules provided the three types of instruction.

Repeated Measures Analysis of Variance (RM-ANOVA) was used to determine interaction effects and practical significance. Where interactions were significant, they were followed by analysis of simple effects and simple contrasts. Otherwise, main effects were tested to evaluate which variables influenced the learning, as measured by scores on the tests.

Discussion

This study found no advantage for explicitly mapping the source and target features when using an analogy. All three types of instruction (no analogy, with an analogy, and with an explicitly mapped analogy) produced the same pattern of learning. Subjects made significant gains, as measured by the post-test after instruction. This

persisted over the two-week gap before the delayed post-test, and students' scores were still significantly above their pre-test scores. Those who knew the least about electrical circuits benefitted the most from all three types of instruction. The explicitly mapped analogy was useful to the students, but not more than the other types of instruction. This is one step of the TWA classroom model for analogy use, a model frequently cited but seldom studied quantitatively.

It is important to note that there may be other advantages for using explicitly mapped analogies, which were not studied. They may be more interesting or understandable to students. It may be that explicitly mapped analogies are valuable for addressing science misconceptions. Other important components and processes of learning may be aided by using mapped analogies. These, and other possible advantages should be studied.

Limitations

There were several limitations of this study. First of all, this study was done within a limited age group. This age group has been previously used, however, in studies of instruction with analogies (Brown & Clement, 1989; Duit et al., 2001; Mason, 2004). Second, there was a single topic or concept used. It may be that analogy use needs to adjust, based on the topic. Third, the instruction modules may not have been different enough to allow identification of interactions or effects. Finally, the instrument used to measure learning may not have been appropriate for identifying interactions or effects. Despite these acknowledged limitations, this study attempted to start filling in the gaps in empirical evidence for how analogies can be effectively used in science classrooms.

CHAPTER 2

BACKGROUND INFORMATION: ANALOGIES AS LEARNING TOOLS

This study is grounded in three bodies of research. First is the research about how students learn and how analogies work for learning. This will be explained from a cognitive orientation. Second is the research that has been done of analogy use in science education. Finally, there is a small body of research about classroom models that have been suggested for educational use.

Operational Definitions

Learning. Knowledge. Cognition. Many terms used in educational research can get in the way of clear understanding. To avoid this, I will use “learning,” “knowledge,” and “cognition” distinctly rather than interchangeably. “Learning” is a change centered in an individual--in understanding of concepts, in skills, in attitude, in schema, in capacity, etc. I will use “knowledge” when referring to the product of learning. “Knowledge” is the purpose of most formal education and is measured in a variety of ways. “Cognition” will be used when describing the complex, interactive system of processes that make up learning.

Analogies. The term “analogy” is often used to describe a variety of phenomena. In general, analogies are mechanisms for showing the relational structure between two systems, domains, or concepts, with varying degrees of similarity among features. Analogical reasoning is a process of aligning similarities between different ideas or systems so information is transferred from one system to another (Duit, 1991; Gentner, et al., 2001; Gentner & Markman, 1997; Holyoak, 2005). Whether implicit or explicit, an analogy is a comparison. In the literature, one side of the comparison is labeled the target

(for example, see Harrison & Treagust, 2000). The familiar side of the comparison is the base (for example, see Glynn, 2008), source (for example, see Kim & Choi, 2003) or analog, which can refer to either the source or the target (for example, see Glynn & Takahashi, 1998). I will use "source," rather than "base," to emphasize my research focus on learning.

Cognitive Orientation

To understand what is known about learning from analogical reasoning, it is necessary to understand what is known about cognition, for "analogy does not occur in isolation; it works in conjunction with other psychological processes" (Dunbar, 2001, p. 318). Learning has typically been seen as either experience-centered and externally driven or mind-centered and internally shaped (Reynolds, Sinatra, & Jetton, 1996). A cognitive orientation takes into account unseen processes, as opposed to a behaviorist orientation which portrays learning as externally driven. While internal processing cannot be observed, scientists accept reasonable and adequate explanations for these unobservable processes, inferred from observations. Many of these inferences are being corroborated as improved technology and medical research provide insight into the workings of the human brain (Holyoak & Hummel, 2001).

Mind-Centered Paradigm

Models.

Information processing model. Within the cognitivist paradigm, many models have been suggested to explain how cognition works. The development of computers gave rise to an information-processing model. The computer is used as a metaphor for human learning, with inputs, processing, and outputs (Newell & Simon, 1972; Reynolds

et al., 1996). The brain's physical neural systems are seen as hardware (Baars, 1986). Processing is described as inputs going into sensory memory. If attention is allocated, the inputs enter into short-term memory or trigger the output of a response. In short-term memory, there is encoding that allowed storage in long-term memory. When information is needed, retrieval takes place, and the information is outputted (Bruning et al., 2004; Driscoll, 1994; Myers, 1989).

Modal model. Information processing models do not explain very well how information is organized and stored. The more generally accepted modal model is of information being processed in a variety of types of memory. Sensory memory provides initial perceptions of incoming stimuli. Then, in working memory, that information is processed and encoded for storage in long-term memory. We know that it is not a simple through-put of information, however. A relationship exists between long-term memory and how we perceive stimuli. In addition two-way communication takes place between long-term memory and the processing that happens in working memory, affected by metacognitive processes, the context, and even by the stimuli themselves (Bolles, 1986; Driscoll, 1994; Myers, 1989).

Working memory. While long-term memory is considered boundless, working memory is limited, in both duration and capacity. The demands placed on working memory can be inherent to the properties or nature of the information, or they can be a function of the activity, context, or characteristics of the learner (Bruning et al., 2004). Different kinds of processing use different amounts of the limited working memory resources (van Merrienboer, & Sweller, 2005).

Research has provided evidence of how the limited resources within working memory are used strategically. Much depends on the attention allocated and the way the information is presented. Some processing of information is automatic and unconscious. Goals, emotions, evaluations, judgments, and perceptions can influence processing. Bargh and Chartrand (1999) explain that automaticity can free up limited conscious capacity and capacity can be shaped by both experiences and volition.

Because allocation of attention affects the processing of information, it is important to know whether it is allocated automatically or can be controlled by the learner. Evidence has been found for both. Studies have found evidence that the learner can make decisions about allocating attention and the environment, such as a text, can have features that influence the amount of attention allocated (Reynolds, 1992). Attention is often allocated and shared, based on competing goals (Driscoll, 1994; Pintrich, 2000).

Decisions about allocating attention are aspects of metacognition. Metacognitive strategies can be modeled and taught, as evidenced by studies on self-efficacy and self-regulated learning (Pintrich, 2000). The important aspect, though, is that learners can select strategies appropriate to a situation and this affects learning. It also means that learners can select strategies that are not appropriate or efficient, especially if they lack the background to decide, do not have goals to do so, make decisions based on inaccurate automatic responses, or have beliefs that contradict the new information.

Long-term memory. Network analogies are most often used to describe long-term memory. The Adaptive Control of Thought (ACT, now ACT-Rational) model describes how categorical information and content are encoded in schema. As information is added and encoded, connections between schema are made. Through this process of spreading

activation, stronger cumulative connections are made (Anderson & Matessa, 1997; Bruning et al., 2004). In connectionist models, units of information are stored, but the connection strength and the distribution of the connections are the important aspects. Familiarity is evidence of a connection being activated (Bruning et al., Nussbaum, 2008).

Driscoll describes how retrieval uses cues or recognition of similarities in the long-term memory, which is organized as a hierarchal network of discrete particles of information. The retrieval could be described with a feature comparison model, a propositional network model, or a semiotic structure model. Information is taken apart, stored, and then reconstructed for retrieval. With this model, all input is stored forever; forgetting is a retrieval problem (Driscoll, 1994).

Schemata provide the organization for information. Anderson and Pearson (1984) explain a schema as a structure, abstract not physical. Schemata can be compared to scripts or procedures in that they construct how knowledge is situated or compared to theories because they predict and influence (Reynolds, 2006). Schemata can be historical, content, beliefs (Anderson, Reynolds, Schallert, & Goetz, 1977) or cultural (Reynolds, Taylor, Steffensen, Shirey, & Anderson, 1982).

Schemata are organized in a hierarchy, represent many kinds and levels of knowledge, and are active and changing (Bruning et al., 2004; Reynolds et al., 1996). As new information is added, processing fits the newer information with the existing schema. Learning is facilitated when clear fits are found and the learner can make the connections. This process requires inference on the part of the learner, constructing of knowledge, and selective attention (Anderson & Pearson, 1984). No text is totally explicit and no conversation is complete; the participants must bring the meaning to

them. Even the simplest schema is very complex in its inter-relationships with other schemata and filled slots.

For understanding the mechanisms of analogical reasoning, we must conceptualize how information is stored. Original information is not stored. Information is stored as declarative or procedural, and it is chunked and encoded in semantic or meaningful units and propositional units, with links that associate and connect the units. Memories are coded for their meaning, semantically, and are retrieved in chunks (Bolles, 1988; Bruning et al., 2004; Driscoll, 1994). What we consider the meaning of a memory is provided by the connections (Nussbaum, 2008). Upon retrieval, they are re-created and influenced by their connections to other memories (Christianson & Nilsson, 1989; Corkill, Bruning, & Glover, 1988; Loftus, 2003). Thus, we use the metaphor of semantic and propositional networks.

It is important to note that schemata are not simply paradigms that shape behavior or beliefs. They are the metaphorical structures that organize knowledge and allow for meaning and comprehension. Learning is an internal process of attending to, evaluating, and fitting information to existing knowledge. Because of this, prior knowledge can facilitate understanding or it can derail it (Anderson et al., 1977). This collection of models explains how new information is received, encoded, connected and stored by a learner and provides explanation for how critical existing knowledge is for meaning and sense making. While acknowledging the importance of background knowledge on learning, these models do not explain all of the processes that are included in cognition.

Transfer. We think of transfer as moving something from one place to another. In the case of cognition, the substance and connections of schemata are moved or copied to

new information or problems. This is manifested when a learner applies skills or knowledge from one domain to another or in a new context (Nussbaum, 1999). Retrieval of information, in order to transfer, is influenced by context, depth of processing, and cues. It is fostered by similarities, modeling, practice, and examples (Nussbaum, 2008).

Influences on Cognition

Bi-directional nature of memory. For understanding how analogies can support learning, it is necessary to understand that working memory and long-term memory are intimately connected. Incoming information is processed and encoded in working memory, based on what is stored in long-term memory. Even affective influences and socio-cultural influences are based on information, attitudes, and skills encoded in long-term memory.

Elaboration. The many strategies that use working memory resources fall under the umbrella of elaboration. Elaboration is the work of creating or strengthening multiple connections among nodes. As information is processed more deeply or through repetition, connections are activated and further connections are made (Flavell et al., 2002; Nussbaum, 1999; 2008). This becomes the focus of many classroom activities and even homework assignments, as students repeat, use worked examples, read new information, and collaborate. Students can be taught strategies that provide elaboration and improve the encoding, retrieval, and application of knowledge. The list of strategies is beyond the scope of the current literature review; however, a few examples are appropriate. Evidence has been provided for strategies such as rehearsal, chunking, and analyzing (Bruning et al., 2004). Students can be provided opportunities to come up with their own organizational structure, helping them learn (Nussbaum, 1999; 2011).

Argumentation (Nussbaum, 2002), problem-solving (Griffin & Jitendra, 2009), reconstructing meaning (Wade-Stine & Kintsch, 2004), worked examples (Salden, Aleven, Renkl, & Schwonke, 2009), self-explanation (Chi, 2000), and student-generated questions (Chin, Brown, & Bruce, 2002) have all been shown to help students develop deeper understanding of concepts.

Scaffolding. In science education, strategies used in guided instruction are often referred to as scaffolding. As Losh and Nzekwe (2011) point out, "Constructs such as 'priming,' 'schema,' or 'selectivity' describing the selection and interpretation of data are now ubiquitous in the cognitive and education literature" (p. 4). Priming and selectivity are examples of scaffolds that can be provided for students. Scaffolds allow students to accomplish something beyond their capacities (Pea, 2004).

Scaffolding is thought to be valuable for a number of reasons. One of the values of scaffolding is that it can provide models of how experts think and the strategies they use (Caliskan, Selcuk, & Erol, 2010). Scaffolding may help decrease the cognitive load on working memory (Salden et al., 2009). It can help learners see the relevant components of the task, model strategies, and assist with mental representation of concepts (Davis & Miyake, 2004), as well as direct attention where it is needed (Duit, 1991). Scaffolding is a strategy for differentiating instruction, based on students' needs and their previous knowledge (Allen & Tomlinson, 2000; Anderson, 2007; Tomlinson, 1999).

Developmental influences. Linked to the postulate that the human brain matures physically, is the observation that cognitive processing develops. Even before Piaget's influential work, educators and philosophers looked for models that would describe this.

Neo-Piagetian researchers, such as Robbie Case, described children being able to handle more and more information and more and more features of a problem. Along with this, develops the skills for integrating them. All of this happens in tandem with increased storage capacity. Case accounted for the unevenness of cognitive development with a model of different kinds of, and generality levels of, domain knowledge. Eventually learners develop the ability to apply information across domains (1992). Halford explained the development differently, suggesting that humans increasingly and predictably learn to create mental models, including analogies, to solve problems (1993).

Siegler used an information processing model, with waves of strategies being accessed and applied, then abandoned. Another model, known as Theory Theory, describes how children develop explanations or theories and then adjust or modify those theories as they continually test them (all researchers described in Flavell et al., 2002).

Socio-cultural influences. A diverse body of research has explored the socio-cultural influences on cognition and development. There is evidence that the environment can impact automaticity and perceptions (Bargh & Chartrand, 1999). Processing, as seen through cognitivism, conceptual change, or any of the variations on these themes, is internal. Socio-cultural researchers present the view that knowledge is not passed from one person to another, but is built through social interactions and tempered by the learning environment (Reynolds et al., 1996). Much of this work is based on Vygotsky's writings. For a socio-culturalist, learning is the changing or transforming of socially shared experience into personalized and internalized knowledge. According to socio-cultural theorists, all learning is social and, while thinking is individual, the social setting allows a window into that thinking (John-Steiner & Mahn, 1996). Vygotsky explained

that the individual and setting cannot be studied separately; instead we must look at the interplay. Each learner has a zone of proximal development or gap between what they know and can do and what they could do or learn. The social setting can be the catalyst or scaffold for learning (Wink & Putney, 2002). It would be difficult to argue that the social setting and/or the environment do not impact learning. However, it is equally difficult to argue that all learning is a social activity.

Analogical Processes

Based on this cognitive framework, I now turn to a description of the processes in analogical reasoning. In order to understand how analogies work, we must not lose sight of the purposes and contexts for various kinds of analogies, for the pragmatic constraints influence how each analogy works. An analogy is a process of transferring information about a source to a target. This cognitive process involves accessing or retrieving the source, mapping the information about the source onto the target, evaluating the match to judge the appropriateness of the mapping, using the mapping to make inferences about the target, and (in learning environments) organizing the new information for future retrieval (Gentner, 1989; Vosniadou, 1995).

Components of Analogies

Source. The source in an analogy should be carefully chosen, as it becomes the basis for learning (Aubusson, 2006; Blake, 2004), a “proto-theory” for the target (Wilbers & Duit, 2006, p. 39). Because the source activates the prior knowledge and shares that knowledge for processing new information, the source influences the learning, misconceptions, and decisions that are made (Markman & Moreau, 2001; Mason, 2004) as it activates schemata in long-term memory.

Ideally, the source for an instructional analogy should be familiar to students. Familiarity leads to less processing time and demand on working memory (Newton, 2003). If the learner is not familiar with the source, there can be frustration and loss of interest (Harrison, 2006). Conversely, interest can be peaked if the source "resonates with the learner's existing experience" and makes sense (Heywood & Parker, 1997, p. 88).

Influences of the source. The source can be used to foster elaboration. Researchers found that, when students had to struggle to understand a source problem, it was more retrievable for solving a target problem. The researchers suggested that a difficult source problem may require building a more abstract representation of the problem space, a representation that could then apply to a new problem or target (Didierjean & Nogry, 2004). This finding fits with what we know about the importance of elaboration.

The challenge for teachers is to know what learners understand about the source. As researchers have pointed out, there is no guarantee that all students have the same understanding of the source or that it matches the teachers' (diSessa & Sherin, 1998; Duit, 1991). One concern is that a student who knows little about the source does not have an opportunity to truly compare or question source and target, an elaboration strategy, but must accept the alignment (Wilbers & Duit, 2006). Like using multiple examples, another strategy that promotes deeper processing, more than one analogy may be helpful in order to tap into enough meaningful knowledge, allowing more information from existing schemata to transfer to the target (Gick & Holyoak, 1983; Vosniadou, 1989).

The source is seldom retrieved intact from long-term memory but often includes components and insertions from other information in memory. All of what we understand about memory, including the relationship between working and long-term memory, capacity constraints (including induced constraints such as stress), and organization of prior knowledge, influence source retrieval. We know that human memory is dynamic, personal, context-sensitive, constructive, incomplete, reliant on perceptions, and affected by reasoning skills (Goswami, 2001; Hmelo-Silver & Pfeffer, 2004; Kokinov & Petrov, 2001; Larkey & Love, 2003; Richland, Morrison, & Holyoak, 2006).

Socio-cultural influences. Different examples of relationships act as priming in different ways for analogies (Leech, Mareschal, & Cooper, 2008). When analogies are used for persuasion, for example, the persuaders are often counting on emotions accompanying the source (Dunbar, 2001). This underscores not only the importance of memory and prior knowledge, but the cultural context of the situation and the learner. This means that analogies are not always normative, but very culturally and collaboratively approached, an important feature because we cannot always easily predict how people will interpret analogies (Bouissac, 2008; Harrison & Treagust, 2000).

Target. The choice of a target forms the purpose for using an analogy. What is known about the source can be mapped to the target. As described above, this can provide concrete mapping for an abstract target or associate known relationships onto unknown relationships. The target becomes a hypothesis to be tested, formed by what is known about the source (Wilbers & Duit, 2006), new information that needs an organizing structure (Mason 1994), or a decision that needs to be made based on a previous situation (Markman & Moreau, 2001).

Similarity between source and target. Surface similarities between the source and target are important for activating schemata. Subjects are more likely to cue the appropriate source if it has similar features to the target (Markman & Moreau, 2001). "Explanatory power of an analogy generally increases as the number of similar features shared by the analog and target increases" (Glynn, 1991, p. 226).

Mapping. Mapping is the process of constructing an alignment of features, relations, or even explanations (Vosniadou, 1989), of systematically making correspondences between the elements of the source and those of the target (Gentner et al., 2001; Glynn, 2008; Glynn & Takahashi, 1998; Holyoak & Thagard, 1989; Thiele et al., 1995), with no regard for the number of shared relationships or even if all of the relationships in the source are mapped with the target (Gentner, 1983; Gick & Holyoak, 1983). In an analogy, the source and target are symmetrical; one is not more important, causal, or dependent on the other (Duit, 1991); however, we usually map from the source to the target. The task is to map information from the source to the target while maintaining the system of relationships that are in the source (Gentner, 1989). The value of an analogy is in identifying that underlying structure or principle that is common to both the source and target (Duit, 1991).

Mapping is based on mental representations of the propositions or relationships of the source and target, symmetrical and non-hierarchical (Wilbers & Duit, 2006). It is a working memory process of connecting what is known about the source with the target (Duit, 1991). We should consider that the comparison is happening within a person's unique schemata, in light of their goals, and within a particular context (Gentner & Markman, 1997). In general, the process involves disregarding most of the attributes of

the objects or concepts, then identifying the relationships before choosing a system of connected relationships over isolated or individual relationships (Gentner, 1983). The best alignments are based on the meaning and goal of the comparison and are not based on syntactic but on semantic correspondence (Markman & Gentner, 2000), as that is how information is organized within long-term memory.

This process taxes working memory in many ways. Any description of analogical mapping has to account for the inhibition of matching surface features and choosing relational structures. In the best analogies, surface similarity is salient enough to aid in recall of information but does not drive analogical reasoning (Goswami, 2001; Vosniadou, 1989). Conversely, when the underlying structure becomes more abstract, more of the surface similarity that helps with retrieval is removed (Gick & Holyoak, 1983). Researchers found that, when the relationships were similar but not synonymous, the processing time was longer. In a followup study, people were given pairs of stories. The stories were remembered on the basis of surface similarities. However, when the subjects were asked to use one story to make inferences about the other, they used the structural similarities or relationships (Gentner, Ratterman, & Forbus, 1993). This preference fits with how we describe the organization of information in long-term memory.

Mappings actually include both similarities and differences (Gick & Holyoak, 1983). People attend to the alignable differences over non-alignable differences (Markman & Moreau, 2001). Many combinations of mappings between a source and target are possible; systematicity, therefore, actually puts constraints on all the possible relationships that could be mapped. The principle of systematicity is that there is a

preference for higher order, more connected relationships. If predicates in the source belong to a system of relationships, they are more likely to be mapped to the target than if they are isolated predicates. If predicates belong to a system of relationships, they are more likely to be mapped with the target (Gentner, 1988; 1989; Gentner, et al., 2001; Gentner & Markman, 1997). Based on a series of studies with adults, it appears that surface similarity may be used for retrieval from memory; however, judging the aptness of a pairing requires understanding the relationships (Brown, 1989; Gentner, 1989; Gentner et al., 1993; Mason, 2004) and ensures that only mapped information is carried to the target (Markman, 1997). It has even been suggested that identifying and discarding the irrelevant attributes is part of analogous thinking (Zeitoun, 1984), more burden for working memory.

A constraint that actually helps working memory processing is that the relationships mapped are parallel in a one-to-one correspondence. In other words, a relationship in the source is mapped only to a single relationship in the target. This bidirectional parallelism is known as isomorphism, and it is critical to shaping the analogy (Klauer, 1989; Markman, 1997). It follows logically that the matched relationships will have matched arguments (Gentner & Markman, 1997; Markman, 1997).

Cross-mapping. This type of mapping also taxes working memory, and a great deal of what we understand about analogical reasoning comes from the study of cross-mapping. Cross-mapping happens when very similar or even identical objects have very different roles in analogous scenarios. Usually, subjects are given analogous situations, graphically. For example, in a first picture, a dog may be chasing a cat, and in a second

picture, the dog is being chased. Because the relationship (chasing) is the same, the scenes are analogous; however, because the dog is first the chaser and then the object of the chasing, cross-mapping happens. Cross-mapping slows people down, evidence that it makes greater cognitive demands on working memory (Gentner & Markman, 1997).

Inferencing and transfer. An analogy works when information from the source is transferred to the target. This is an inductive process (Brown, 1989; Harrison & Treagust, 2000; Klauer, 1989). This is possible because a system of associations in the source can be mapped to a system of associations in the target (Glynn et al., 1989). When students are taught about cells, for example, they are often asked to consider the relationships between components in a town or a factory, the relationships between structures and their functions. This previous knowledge of a town or manufacturing system is then mapped onto cellular structures. The relationship between the mayor's office and the rest of the town is mapped onto the nucleus and the other components of the cell. Of course, there are unshared attributes, which limit the similarity between the source and the target (Venville & Treagust, 1997). The mayor's office has no function, for instance, analogous to the nucleus' function in cellular reproduction.

The term "transfer" is used in analogy literature to describe the process of making inferences about the target, based on the mappings from the source. The processes of mapping and transfer are iterative, consisting of mapping an alignment, transferring the information, checking the alignment, and identifying the non-alignable components, all constrained by the goals and context (Clement & Gentner, 1988).

The source provides information for inferences about the target through mental images of the relationships involved (Wilbers & Duit, 2006). Inferences are based on the

underlying relationships in the analogy (Clement & Gentner, 1988; May et al., 2006). We fill in what we do not know about the target from the source, a type of structural completion (Markman & Moreau, 2001; Newton, 2003).

Building schemata. The most salient relationships, such as causation, are carried to the target. Researchers suggest that a mental representation is copied, with all of its attributes and predicates attached, then substituted into the unknown target to form a new mental representation about the target (Holyoak, 2005; Markman, 1997). The process includes a re-representation in the target and building a more abstract schema. Unless the knowledge is actually re-represented, the transfer would be literal and interfere with an accurate mental model of the target concept. Strong transfer depends on relational correspondences, while retrieval depends heavily on surface similarities, so re-representation takes place as the relationships that underlay one set of features must associate with different features in the target (Kurtz et al., 2001). Either the source projects meaning onto the target or parallel meanings develop (Gentner et al., 2001). The inferences about the target become new schemata that are then encoded in memory, shaped by the goals of the subject and strengthened by connections with previous knowledge (Gentner, 1989; Holyoak, 2005).

The importance of existing schemata cannot be downplayed. For example, when white blood cells are analogous to soldiers, young children infer that the white blood cells will kill germs and that germs are bad. However, they usually rely on the schemata they have about soldiers and infer that the white blood cells could get hurt in this battle (Vosniadou, 1989).

Developmental aspects. Piaget saw analogy use as evidence of a developmental stage, and said that children at the beginning of the formal operational reasoning stage would be able to categorize, use inclusion, compare, and see similarities in relations. Formal operational reasoning would be needed to understand multiple relationships, such as a:b as c:d (Goswami, 1991; 2001; Vosniadou, 1995). Children, especially young ones, map surface features (Loewenstein & Gentner, 2001), a kind of functional fixedness that interferes with analogical reasoning (Solomon, 1994). Gentner coined the term "relational shift" to describe the shift in focus from surface features to underlying structures; children start out using surface features to interpret an analogy and change to an interpretation based on relationships. In her studies, children between five and six years old could interpret significantly fewer relationships than nine- and ten-year-olds and adults (Gentner, 1988; 1989); this was seen as evidence of a developmental component to analogical reasoning (Holyoak, 2005).

However, other researchers, most noteworthy being Goswami, provide evidence that analogical reasoning starts in infancy and is naturally used well before Piaget's formal operational stage. For example, my barely four-year-old grand-daughter, much too young for Piaget's formal operational stage, was cutting paper into small pieces with scissors. She noticed her baby sister step on a cracker and smash it. "Grandma, my scissors are like Tallie's foot," she informed me.

There are four possible explanations for why analogical reasoning is spotty in young children. First, working memory capacity increases as children develop. Second, understanding of relationships develops. Third, content knowledge develops and

increases. Fourth, the task of analogical reasoning becomes understood better as a child grows up.

Limits to working memory increase as children develop. Young children, for example, struggle to hold enough information in memory to compare possible sources, let alone use that information (Kim & Choi, 2003). Older children can compare more relationships than younger children (Goswami, 2001). Working memory capacity is critical for being able to notice the relationships, for mapping (Tohill & Holyoak, 2000), to retrieve prior knowledge from long-term memory, to inhibit superfluous information (Leech et al., 2008), to build mental representations, and to compare relationships (Goswami, 2001). Even adults, when working memory is taxed, revert to surface mappings (Tohill & Holyoak, 2000).

Perhaps young children map on surface features because they do not have well-developed understandings of relationships (Brown, 1989; Goswami, 1991), understanding that is known to be developmental (Smith, 1989). Relationships, after all, require more complex schemata than do surface features. In one study, very young children had difficulty lining up objects from smallest to largest. However, when they referred to the objects as the “daddy,” “mommy,” and “baby,” they had no difficulty with the task (Mix, 2008). Young children are able to use stories with morals (explicit relational structure) analogously better than stories without explicit relational structure (Goswami, 2001). Children as young as two and three years old can use relationships for inferences, even in the absence of surface similarity, if the relationships are pointed out to them (Brown, 1989; Goswami, 1991).

Understanding relationships may be tied to content knowledge. When a child has more knowledge on which to draw, it may be more likely that an analogy can be used. In several studies, the classical analogies used by Piaget were changed to pairings very young children would recognize, and they were much more competent than was predicted for their ages (Goswami, 2001). Studies of experts (Clement & Gentner, 1988) using analogies and research with young children both provide evidence of how important the content knowledge is (Leech et al., 2008). Dunbar (2001) points out, however, that in natural settings both children and adults are more likely to use relationships than they do in laboratory or contrived settings, disputing that content knowledge is always crucial.

Finally, children are better able to use analogies when they understand the actual task. When young children understand the "rules of the game" or have procedural knowledge, their competence with analogies increases dramatically (Brown, 1989). The development of analogical reasoning parallels development of metacognitive strategies; when children can reflect on their knowledge, they become more capable of using analogies (Brown, 1989; Goswami, 1991).

Socio-cultural aspects. It is important, when using analogies, to acknowledge the cultural and social context of prior experience. Most models depict analogical reasoning as an individual, internal process, and miss the possibilities associated with input from the contextual group. Teachers and parents use analogies naturally when working with children. Most tend to use analogies that would include a source or base that is familiar to the child, and it is important to consider what background knowledge the child has. Analogical reasoning can be mediated by the social group as well as by the cultural background of a learner (Valle & Callanan, 2006).

Instructional Tools

Types of Analogies

When studying how analogies are used for instruction, the variety of analogies is problematic. It is necessary to identify which type of analogy is being used and the purposes for using the analogies. To classify analogies, I divide them into four types: naturalistic, reading, classical, and instructional analogies. In this section, each type is described, along with the purposes for which it is used, and examples are provided from analogy research. The research examples are not exhaustive; rather, they were chosen to be typical of the way research has been conducted on each type of analogy. Because of a specific interest in analogies used in science education, the instructional analogies group is given more attention than the other types, with no apology for the unbalanced treatment.

Classification schemes. Other classification schemes for analogies exist in the literature; these are based on each researcher's purpose and specific research problems. For example, Gentner (1983) classified comparisons along a continuum from literal similarity, in which there is an exact match between features and relationships, through anomaly, in which there is no match between features or relationships. Gentner was studying the mapping or comparing that happens when considering two concepts, objects, or systems, so this type of classification was needed. Other researchers approached analogies from a naturalistic perspective of how they are used in science classrooms. With no explanation given for the classification system used, Dagher and Crossman (1992) identified ten types of explanations, including analogies. Later, focusing just on analogies, Dagher (1995b) distinguished: (a) compound analogies, using more than one

source; (b) narrative analogies which were very storylike; (c) procedural analogies, giving instructions for accomplishing something; (d) peripheral analogies, as the teacher elaborated; and (e) simple analogies, which needed further development. At the same time, she pointed out that the domain in which she worked influenced the descriptions of analogies.

The most extensive classification systems for analogies appear in analyses of science textbooks. In these analyses and other studies, analogies are classified by their structure and components, such as being extended or elaborate (Glynn & Takahasi, 1998; Orgill & Bodner, 2006; Paris & Glynn, 2004; Zheng et al., 2008), auditory or text-based (Markman, Taylor, & Gentner, 2007), using surface features or structural relationships (Gentner & Kurtz, 2006; Nokes & Ross, 2007; Richland et al., 2004), difficulty level (Roccas & Moshinsky, 2003), and various degrees of abstractness (Curtis & Reigeluth, 1984; Newton, 2003; Orgill & Bodner, 2006). Analogies have also been classified as to whether they are student or teacher centered (Oliva, Azcarate, & Navarrete, 2007; Richland et al., 2004). None of these classifications, however, exploit the purposes for which the analogies studied were made, a key feature of studying efficacy. Richland et al. (2004) identified four mathematics goals for the analogies they studied. Their goals of "being a math student," "concepts only," "concepts and procedures," and "procedures only" (p. 45) are so specific to the mathematics classroom that they are not useful for classifying the wide variety of analogies. Holyoak (2005) divides the research related to analogies into the "psychometric tradition" (p. 118), the study of metaphor, and "knowledge representation" (p. 12 a). His classification system introduces a tangent, with the study of metaphor, leaving two categories of analogies.

None of these previously used classifications were appropriate for this study. I chose to examine four purposes for analogies in general and use those purposes to delineate four types of analogies.

Naturalistic Analogies

Description of naturalistic analogies. Humans seem to use analogies naturally and frequently. “Hardly a day elapses without encountering one—either in print (from Plato to Einstein to Agatha Christie) or in everyday spoken language” (Curtis & Reigeluth, 1984, p. 99). Very young children use spontaneous analogies (Gentner, 1988), and research with children has led more than one researcher to suggest that analogical reasoning may be tied to development as children create mental models that are analogous to the world (Goswami, 1991; Vosniadou, 1995). Holyoak (2005) provides examples of the use of analogies in scientific endeavors, mathematics, law, and public policy.

Naturalistic analogies are sociocultural in nature. Some analogies have become entrenched in a particular culture, at which point they are used as metaphors. The word “fire” probably was used in analogies mapped to such concepts as knowledge, love, and envy and is now part of our metaphoric vocabulary (Gentner et al., 2001). The sociocultural nature of naturalistic analogies is important to remember; we can make a mistake in assuming that shared understanding exists when it may not.

Purposes of naturalistic analogies. In many aspects of our lives, analogies are used to clarify and put into words a concept (Dagher, 1995a). Parents and caregivers naturally use analogies for explaining concepts or events. A benefit of this is that children become encultured to see analogies as an accepted form of communication (Valle &

Callanan, 2006). Analogies are also used for predicting future situations, based on past events (May et al., 2006). We use analogies for describing both abstract and concrete concepts, we provide fables and parables as warnings, we use analogies as literary devices, we use analogies for efficient communication, and we use past experiences as the basis for making decisions. All of these are analogous situations, in the broadest sense of the term.

While "naturalistic analogies" may not be a sophisticated label, there are some very sophisticated uses of analogies in the everyday world. In scientific communities, in particular, "analogical thinking is a key component of all aspects of scientific reasoning, ranging from hypothesis generation to experimental design, data interpretation, and explanations" (Dunbar, 2001, p. 315). Scientists use analogies for discovery, experimentation, explanations, and evaluation of explanations. Many creative discoveries have been made through analogical reasoning, including the invention of Velcro®, that lightning behaves like other electricity, the ring structure of benzene, and even the mind as a computer so popular in cognitive science (Holyoak & Thagard, 1995).

Scientific work obviously involves learning; it could easily be argued that the natural analogies used by scientists could be classified with my fourth group, instructional analogies. This is an admittedly personal distinction; my research interests focus on science education, so it is important to group together the research that provides evidence for how children learn through analogies.

Examples of research involving naturalistic analogies. Dunbar and his colleagues have studied scientists in their work environment for many years, documenting laboratory work and planning meetings as well as interviewing scientists.

Simultaneously, they did controlled tests on aspects of scientific thinking. While the purpose of these studies was to describe how scientific endeavors unfold, Dunbar points out a large discrepancy between how analogies are generated in naturalistic settings and how they are used and generated under controlled research settings. He points out that research can remove the many other important factors that work alongside analogical reasoning in scientific work. Natural processes, such as elaborate encoding and goal-setting, may not serve their purposes for learning (Dunbar, 2001).

Valle and Callanan (2006) found analogies often used in parent and child conversations. While visiting science museum exhibits, parents pointed out analogies, using sources they thought would be familiar or of interest to their children. While helping with homework, parents followed the same patterns. In both situations, parents used analogies that used relational similarities and explicitly mapped the relationships for their children. After the homework assignment, a positive relationship was found between parents providing analogies to explain and their children's understanding of the concepts.

Other important aspects of naturalistic analogical reasoning in children have been discovered through research. First of all, by third grade, many children exhibit the same uses for spontaneous analogies that experts within a domain do. They naturally use analogies for predicting and explaining (May et al., 2006). Goswami's studies of children using analogies led her to suggest that there may be a developmental change from perceptual use of analogy, starting in infancy, to a conceptual use as children mature (2001). Gentner (1988) found evidence for a relational shift, or point in a child's

development where analogical reasoning shifts from comparing surface features to seeking out the underlying relationships or roles.

Analogies are an accepted part of our everyday lives. We use them in so many different ways, from cultural icons to scientific insight, that it would be difficult to catalog naturalistic analogies completely. Analogies permeate our thoughts so completely that it is accepted by many researchers that analogical reasoning is an important aspect of cognition. At the far extreme is the view that "every concept we have is essentially nothing but a tightly packaged bundle of analogies" as we chunk information and go through life comparing new information to existing (Hofstadter, 2001, p. 300).

Reading Analogies

Description of reading analogies. At the basic phonemic level, words consist of sounds, corresponding to letters or groups of letters. The next higher level is the syllabic level, where there is a beginning sound (onset) and middle and ending sounds (rime). A reading analogy, also call a rime analogy or orthographic analogy, is the mapping of an onset and rime onto an unknown word. For example, the word "beak" maps to the word "peak." These rime analogies are more common than onset analogies, such as "bean" mapping to "beak" (Ehri, Satlow, & Gaskins, 2009; Goswami, 1991; Wood, 2000).

Purposes of reading analogies. During the process of learning to read, children must develop phonological awareness and be able to look at the component phonemes in words. Orthographic analogies let early readers use a known word to read an unknown word, promoting word recognition, important to reading development (Kamhi & Laing, 2000; Wood, 2000). Synthetic phonics instruction has the children sound out each phoneme and then blend them together; analogies, however, teach children to use what

they have already learned for parts of the words (Erhi et al., 2009). Reading analogies are, therefore, helpful when to learning to read (Farrington-Flint, Wood, Canobi, & Faulkner, 2004).

Examples of research about reading analogies. Much of the research on the orthographic analogies has been based on the debate over whether students should learn to read in whole language or explicit phonics programs. Out of this has come a divide about the importance and efficacy of using orthographic analogies; the sound structure (phonological priming) may be used, rather than the physical similarities of the words. There is disagreement about the size of the phonological units used by students and at what point in their reading development these units are important (Roberts & McDougall, 2003). Wood and colleagues (Wood, 2000) gave children a battery of tests and then analyzed the results, with multiple regression analyses, to determine the contributions of different factors on reading scores. Orthographic analogy was associated with the largest variance. Rime detection was associated with using orthographic analogies, but so was reading experience and phonemic awareness. This study provided more evidence that orthographic analogies are an important part of learning to read.

Walton and Walton (2002) addressed the question of how rime analogy develops in the very first stages of reading, by experimentally isolating rime analogy strategies from other pre-reading strategies. They found a relationship between rime analogy instruction and phonemic skills needed for reading instruction. They found that children were able to generalize rime analogy use to rimes they had not seen before. In addition, many of the children naturally developed skills in rhyming, initial phoneme recognition

and matching of letters and sounds. They propose that rime analogy is worthwhile for children in the very first stages of learning to read.

On the other hand, Roberts and McDougall (2003) experimented to tease apart the phonological, phonological and orthographical, and orthographical analogies with beginning readers. They found that students used phonological units, or rhymes, rather than looking at the word as an onset and rime, analogous to a new word. Children were very good at using every phoneme in the words and blending them to understand the words. They concluded that students actually use a variety of strategies, and that these vary from instance to instance and context to context.

Classical Analogies

Description of classical analogies. The classical form of an analogy is to notate that A is to B as C is to D, often written A:B::C:D. This notation indicates that D is related to C in the same way that B is related to A (Holyoak, 2005). An example of a classical analogy is bird:nest::human:house. The relationship between a bird and a nest is the same relationship as that between a person and a house, the relationship of residing. The same relationship can be shown as predicates (Gentner, 1983, 1989): OCCUPY (human, house) and OCCUPY (bird, nest). A classical format can be used with an arithmetic analogy, such as 4:8::3:6 or can take the form of pictures rather than words. Work with children, for example, often requires them to look at Pictures A and B, then find a picture that shows the same relationship with Picture C. For example, a picture of handlebars and a picture of a tricycle would have the same relationship as a picture of a steering wheel and a picture of a car. The classical form can also be used with stories and fables (Gentner et al., 2003), proverbs (Markman et al., 2007), and models (Gentner,

1988; Loewenstein & Gentner, 2001). The important distinction is that the relationship between the first pair is the same as the relationship between the second pair. This structure of classical analogies makes them distinct and precludes any need for surface similarities. It is actually difficult to think of attributional similarities between a nest and a house; the similarity is in the relationship with the occupant.

Another important feature of classical analogies is that both pairs are familiar, distinctly different from analogies in which there is a known base or source and a less familiar or to be learned target. While classical analogies most often use higher-order relationships that require understanding of relationships among relationships, such as cause and effect (Gentner, 1988; Holyoak, 2005), there are usually fewer mappings needed (Collins & Burstein, 1989).

Purposes of classical analogies. The relationship mapping required in classical analogies is useful in measuring intellectual capability. Classical analogies have traditionally been used on intelligence tests and the positive correlation between analogical reasoning, using classical analogies, and measures of intelligence, has been well documented (Goswami, 2001; Holyoak, 2005). A classical analogy measures more than vocabulary as it requires one to understand the relationship between the pairs.

Classical analogies have often been used and validated for ranking intelligence and predicting success in academic fields. Research has been conducted on the cognitive processes involved and how individuals differ in solving (Roccas & Moshinsky, 2003). Until 2005, the Scholastic Aptitude Test (SAT) for college entrance had an analogies section (Cohen, 2005).

The Raven's Progressive Matrices Test is an example of the classical form of analogy. It uses geometric shapes and the subject must determine the visiospatial relationships; the RPM is a good measure of *g* as described by Spearman. The RPM requires more mappings than other classical forms of analogies. To solve it, the subject must be able to map relationships between size, color, and shape, often in the same analogy, and the relationship can take the form of a progression (Cianciolo & Sternberg, 2004; Jaarsveld, Lachmann, Hamel, & van Leeuwen, 2010).

Classical analogies have been used for a great deal of research about analogical thinking, also. Most of Gentner's work on structural mapping, which sets out the conditions and parameters for mapping relationships, was done using classical analogy structures (Gentner, 1983, 1988; Gentner & Kurtz, 2006; Kurtz et al., 2001). Studies on development of analogical reasoning in children have also used the classical format, often with pictures or models (Goswami, 2001; Loewenstein & Gentner, 2001; Vosniadou, 1995).

Classical analogies can also be used for learning. If given two different situations, the underlying principle or relationship can be figured out. This has been shown to help students understand causal relationships especially (Kurtz et al., 2001; Mason, 2004). I chose to classify this use as a classical analogy because the examples being compared are both known to the learners or at least enough is known about them both that the relating principle can be found.

Most computational models of analogy use a classical format. During the 1980s, Gentner and her colleagues developed the Structure Mapping Engine (SME), which can map the relationships between two concepts (Forbus & Gentner, 1989; Gentner, 1983,

1989). The Analogical Constraint Mapping Engine (ACME) was developed to include constraints on the amount that can be processed at one time (Holyoak & Thagard, 1989). The Connectionist Analogy Builder (CAB) also included constraints analogous to working memory (Larkey & Love, 2003), as does the Learning and Inference with Schemas and Analogies (LISA) model, which uses semantically based representational networks (Holyoak & Hummel, 2001).

Examples of research using classical analogies. Much of what we know about analogical reasoning has been learned with the use of classical analogies; fewer mappings in the classical format make the basis for research more doable (Holyoak, 2005). We usually rely on Gentner's structure mapping theory to describe the rules of analogical reasoning. This theory includes the primacy of relationships over attributes and the dominance of higher-order relationships in mapping (Gentner, 1983). We know from research that people tend to make a one-to-one mapping correspondence between the base and the target based on roles of the attributes. People also prefer to map systems of relationships, rather than isolated features, when carrying information from one side of an analogy to the other. When subjects wrote out descriptions of objects and then had to interpret analogical comparisons containing those objects, the descriptions contained attributes while the interpretations were based on relationships (Gentner, 1989). Children were asked to transfer a story to different characters. When the story had a systematic structure of underlying relationships, children were better able to transfer the story to cross-mapped characters (Gentner & Toupin, 1986). Cross-mapped characters are those that do not share attributional or surface features. For example, a chipmunk and a squirrel

would share many surface features; a chipmunk and a fish would not. Researchers found that older children were less reliant on the surface features.

Using classical analogies, Roccas and Moshinsky (2003) teased apart the features that contribute to the difficulty of analogies. They looked the contribution of the knowledge components (word rarity and whether the analogy can be understood with the inherent meaning in the words or needs outside information) and the process components (negativity in the relation, order of the words (natural or not), and direct or indirect relations). These components in 104 analogies were rated by expert judges. The rarity of the words, the inherent meaning, negativity in the relation, and order of the words contributed to the analogy difficulty; together they explain a small but significant part of the variance of item difficulty. They concluded that analogies measure, at least in part, cognitive ability, not just knowledge. Student cognitive ability, however, has seldom then been considered in studies of analogy use.

In an attempt to better understand working memory, Tohill and Holyoak (2000) studied how analogical performance would be affected by an induced state of anxiety. They hypothesized that increased anxiety would tax working memory capacity and lead to a decrease in relational mappings and an increase in attribute mappings. They used cross-mapped pictures, so that the same object takes on a different role in a second picture, and had participants answer questions about the cross-mapped pictures. They found that “anxiety led to a systematic shift from relation-based to attribute-based responses” (p. 37) even when subjects were asked to specifically find relationships. This provides evidence that analogies require cognitive resources, which are limited by the capacity of working memory.

Instructional Analogies

It should be obvious that many types of analogies are used in learning situations. However, there are times, especially in a K-12 setting, that analogies are specifically used to teach concepts. These are the analogies I classify as "instructional analogies."

Description of instructional analogies. There are three features which distinguish instructional analogies from other types. First, instructional analogies use a base, analog, or source which is already familiar to the learners. Known information about the base is then transferred as inferences to a less well-understood concept, the target (Clement & Gentner, 1988; Davies, Nersessian, & Goel, 2005). This further explains the importance of underlying relationships over surface features (e.g., Gentner & Kurtz, 2006; Kurtz et al., 2001; Mason, 2004). The surface features of the base are not what teachers want transferred to the lesser known target. Children, as they mature, must actually be able to inhibit the tendency to compare surface features if they are going to reason analogically (Richland et al., 2006). For example, when a teacher successfully presents a city as an analog for an ecological community, the physical features of city components such as streets, buildings, merchants, and customers are not used in making inferences about the ecological community. Rather, the roles of the infrastructure, shelter, consumers and producers transfer to the appropriate components of the ecological community. This means that the roles of streets are mapped to pathways, the purposes of buildings are mapped to shelter, the work of merchants or manufacturers is mapped to producers, and the role of customers is mapped to consumers.

Several researchers have found evidence of how important previous knowledge of the source is (Curtis & Reigeluth, 1984; Dagher, 1995a; Glynn, 1991; Thagard, 1992).

This feature of instructional analogies can also be a danger. A community or group shares a tacit background of accepted knowledge. Teachers, as part of their professional community, have much different understandings than their students, and individual students may have very different conceptions than the group's. A teacher cannot assume that all children have a uniform understanding of the source and must keep in mind that all representations are unique to a person and a time (Duit et al., 2001; Markman & Gentner, 2000; Thiele & Treagust, 1994). In interviews with textbook authors, Thiele and Treagust found they expected that teachers would make sure that students understood the bases used. Orgill and Bodner (2006) point out that there is little evidence that this happens in classrooms. It should also be noted, though, that learning has been documented when two partially understood phenomena are used analogously (Brown & Clement, 1989; Clement, 1993; Kurtz et al., 2001; Mason, 2004).

Often the base is more familiar than the target in the sense that it is more concrete (Bryce & MacMillan, 2005; Dagher, 1995a; Glynn, 2008; Heywood, 2002; Hutchison & Padgett, 2007). Studies of analogies presented in science textbooks show that this appears to be important in science education. In most studies, the majority of the analogies mapped a concrete base onto an abstract concept. For example, the inner workings of a cell are very abstract for children. Teachers often provide a concrete source, such as a town or a factory, to help their students understand the functions of cell components. The proportion of concrete bases varies, though, with the grade level and subject matter (Table 1).

The importance of the mapping between familiar and unknown or from concrete to abstract is critical for the second feature of instructional analogies. They provide a re-

organization of knowledge to integrate the new information and facilitate access and retrieval of knowledge from memory (Chiu & Lin, 2005; Duit et al., 2001; Flick, 1991; Glynn, 1991; Glynn & Takahashi, 1998; Kokinov & Petrov, 2001; Kurtz et al., 2001; Mason, 2004). Evidence suggests that instructional analogies are helpful because students can build mental representations (Blake, 2004; Coll, France, & Taylor, 2005; Davies et al., 2005), and they may provide elaboration though the redundancy of the mapped proposition, especially in the deeper relational structures and the constant back and forth between old and new information (Duit et al.; Paris & Glynn, 2004).

Table 1

Percentage of Concrete-to-Abstract Mappings in Science Textbooks

Level	Content	% Concrete to Abstract Analogies
Elementary	All sciences	40%[a] - 82%[b]
Secondary	Chemistry	87%[c]
Secondary	Biology	62%[d]
Post-secondary	Biochemistry	>90%[e]

[a] Newton, 2003
[b] Curtis & Reigeluth, 1984
[c] Thiele & Treagust, 1994
[d] Thiele et al., 1995
[e] Orgill & Bodner, 2006

The final feature of instructional analogies is that they usually involve more than single words or short phrases. Recall that classical analogies are often simply sets of words, such as “steering wheel is to car as handlebars are to tricycle.” Instructional analogies, however, because they are transferring the relationships and roles from a base to a target, usually are more lengthy (Glynn, 2008) and, in fact, much research has been done on how much detail is needed in instructional analogies (e.g., Glynn, 2008; Glynn, Taasoobshirazi, & Fowler, 2007; Glynn & Takahashi, 1998; Klein et al., 2007; Paris &

Glynn, 2004; Trey & Khan, 2008; Zheng et al., 2008, as well as the previously discussed textbook analyses).

Not all instructional analogies are detailed. Some have actually become so entrenched that it is possible the analogy has actually become the meaning for some students (Heywood, 2002; Holyoak & Thagard, 1995). Some concepts rely on analogies to the point that they are almost always described in terms of their analogies. Descriptions of subatomic particles moving are, for example, are difficult to even imagine without a solar system model. Analogies become so common in certain subjects that their use is not only expected but ubiquitous (Orgill & Bodner, 2006; Venville & Donovan, 2006). Electrical current, for example, is referred to as flowing, even when a water movement analogical source is not being consciously invoked.

Purposes of instructional analogies. Instructional analogies have been used for a multitude of purposes, including conceptual change or ontological shifts in knowledge, problem solving, and persuasion. I chose the label "instructional analogies" because these analogies are all used in the learning of something, or, in the case of persuasive analogies, in a change of behavior based on information. In short, they serve as scaffolding for learning, which may be helpful to different degrees for different students.

Dagher, Thiele, Treagust, and Duit (1993) point out that the purpose of science education is not to repair students' concepts, but to move them towards more canonical understanding. In science education, it is common to discuss the goal of conceptual change. Researchers have argued long about what constitutes conceptual change (e.g., Dole & Sinatra, 1998; Posner, Strike, Hewson, & Gertzog, 1982) and what actually changes. Vosniadou and her colleagues describe cohesive, generative, and explanatory

naïve theories, which qualitatively change to align with scientifically accepted explanations (Vosniadou, 1994, 2007; Vosniadou & Ioannides, 1998). An opposing view is that naïve concepts are disconnected and need to be organized in alignment with scientifically accepted explanations (diSessa, 1998). Chi suggested that conceptual change is a process of ontological shifting in understanding (Chi, 1992; Chi, Slotta, & DeLeeuw, 1994). It is beyond the scope of this literature review to analyze the evidence for each. Suffice it to say, a major purpose of analogy use in science education is for some form of conceptual change or increased content knowledge (Chiu & Lin, 2005; Dagher et al., 1993; Duit, 1991; Glynn, 1996; Glynn & Takahashi, 1998; Heywood, 2002; Orgill & Bodner, 2006; Vosniadou, 2007; Zheng et al., 2008). Vosniadou states that, because of the mappings and transfer that happens, "analogical reasoning [is] a central mechanism in cognitive development and in knowledge acquisition" (1995, p. 298).

In using instructional analogies for learning new concepts, the base is usually given to students, rather than retrieved as Holyoak (2005) describes in his model of analogical reasoning. This is distinctly different from using analogies for problem solving. Problem solving with analogies requires conceptualizing the target problem, retrieving the correct source based on relational or deep structures, and transferring the base solution to the target problem (Gamo, Sander, & Richards, 2010; Kokinov & Petrov, 2001). Experts in a domain are known for being able to use analogies when solving problems, usually spontaneously (Clement, 1988, 1998). In problem-solving, there is a search through the problem space for ways to reach the goal state (Mayer, 1992). In

successful analogical problem solving, this search often produces retrieval of a previous solution that fits the constraints of the novel situation.

The seminal example of analogical problem solving is the Gick and Holyoak (1980, 1983) series of studies on whether subjects could use a solution in a story (troops converging from different directions on a site) to solve an analogous problem (the need for radiation convergence on a tumor). Retrieval of the analogous solution was poor; subjects needed hints about using the analogous story or the opportunity to solve the first story problem for themselves.

Since this study, researchers have shown that problem solving can benefit from making the relationships more salient (Gentner & Kurtz, 2006), comparing a variety of base solutions (Gamo et al., 2010; Gentner et al., 2003), using a procedure in a variety of contexts (Novick & Hmelo, 1994; Sandifer, 2004), connecting solutions conceptually (Clement, 1998), and having strong retrieval cues (Richland & McDonough, 2010).

A particular type of problem-solving using analogies is known as case-based reasoning (CBR). In business, law, and medicine, it is common to teach through the use of cases which highlight the underlying structure of the situation or problem. The students are then expected to transfer the answer or solution from one case to a novel situation (Gentner et al., 2003; Kolodner, 1997; 2002a; 2002b).

A final purpose of instructional analogies focuses on persuasion, a slightly different goal than learning or problem-solving; however, a change in the organization of information or change in behavior based on that information is being sought. Analogies are used to frame politics, policy making, choices, and advertising (Dunbar, 2001; Holyoak, 2005; Markman & Moreau, 2001). Framing has powerful effects on the choices

people make (see Stanovich, 2010 for a good overview). Markman and Moreau use the example of the domino analogy used to frame the need for American intervention during the Cold War. Most people were familiar with the idea of a standing trail of dominoes; when one goes over, it starts a chain of falling dominoes. As countries "fell" to communism, the fear was planted that more and more countries would follow. As people make choices, analogies could actually frame the consideration sets from which they make decisions, although there is not yet empirical evidence for this.

With the emphasis on assessment in the world of education, a fourth purpose for instructional analogies could be proposed, that of evaluation. Generation of an analogy involving a concept, requiring students to provide a detailed mapping, could possibly be used to assess students' conceptual framework. For example, after a lesson on taxonomic classification, students could be asked to develop analogies for the hierarchical system. If students were required to map the relational structures, the teacher could gain insight into how the students organized the information (Chin, Brown, & Bruce, 2002; Sandifer, 2004). Further research is needed of the efficacy of using analogies in both summative and formative assessments.

Examples of research about instructional analogies. Much research has been done on how analogies can be "pedagogically effective," to use Glynn and Takahashi's phrase (1998, p. 113). Chiu and Lin (2005) did a study with fourth-grade students, not only to see if presenting an analogy helped them learn the basic concepts of electricity, but to tease out whether the learning was an ontological shift or conceptual change. They had four conditions: single analogy, similar analogies, complementary analogies, and no analogies (control). All of the groups outperformed the control group, and the

complementary analogies group was significantly different than the others. They reasoned that the interventions that provided multiple perspectives were most effective. They also found that students expressed predicates that could be classified as matter, processes, and mental states (Chi et al., 1994), before and after the intervention. The complementary analogies group was the only one that statistically demonstrated a difference in ontology, moving towards more process predicates. In other words, they provided evidence for children learning about electricity through the use of analogies, as well as evidence of small ontological shifts.

Some of the most interesting studies of analogies have been done in physics, using experts. Clement (1998) used a series of case studies to determine how experts use analogies in solving problems. The subjects were experts in domains that require problem solving, advanced doctoral students and professors in technical fields, but not experts, *per se*, in the fields for the problems they were given. He found that those with expertise in problem solving used four steps, although not always in a particular order: (a) generate a tentative analogous relation; (b) judge the aptness or appropriateness of the analogy; (c) examine the known half of the analogy; and (d) transfer conclusions, principles, or procedures from the known analog to the problem. The experts retrieved or generated analogs based on structural relationships or underlying principles, rather than surface features. They also spent an inordinate amount of their problem solving time on questioning and judging the aptness of the analogy before they used it. Clement points out that this is counterintuitive to the commonly held view that analogies are shortcuts for instruction because they present a system of relationships in one representation. Clement discusses how this fits in with his work on bridging analogies, in which students move

through a series of analogies to a more scientific understanding, and he provides evidence of the efficacy of this approach.

Dunbar (2001) and his colleagues did extensive qualitative studies of persuasive analogy use in politics, specifically during a referendum on Quebec independence in 1996. They analyzed politicians' and journalists' analogies in newspapers, over 200 analogies in 400 articles in the last week before the referendum vote. They classified the targets and bases semantically, rated the emotional connotations of the bases, and determined whether the targets and bases were from closely related or distant domains. Analogies were used by the politicians and journalist both to argue for a side and to point out dangers of the other side. The targets and based were from such diverse categories as farming, athletic competition, and religion. Most of the sources used by politicians were highly emotional, and positive emotion was invoked for their side and negative emotion invoked by analogies used to argue against their stance.

Analogies: Complex Learning Opportunities

In summary, analogical reasoning is a group of complex, non-linear, cognitively taxing processes, rather than a single skill. Dunbar concluded that "analogy is much more than a mechanistic thought process" (2001, p. 32). We know how critical previous knowledge is for learning. Humans store and organize information in long-term memory, and that information is used for further learning. From a cognitive orientation, analogies are specifically designed to allow students to bring their organized network of prior knowledge to a new concept and perform several functions.

First, analogies activate schemata relevant to new information. Activation of a chunk of related information is efficient. In addition, by using an analogy, the teacher can

direct what is used for background knowledge. Second, an analogy provides an organizational system for new information. It allows already strong, meaningful connections to be tied to new information or to assist with changing misconceptions. Third, analogies can provide mental models that connect abstract principles or un-experienced processes to more concrete, meaningful schemata. So much of what we do in science education is abstract or invisible. Models become critically important as children move towards scientific understanding. Fourth, using analogies provides an elaboration strategy. If students can carefully map from the source to the target, they will experience deeper processing, which we know leads to stronger learning gains. Analogies can provide the keys to unlocking treasure chests of previous knowledge that can promote learning.

Guided Instruction is Valuable

This study rests on the value of guided instruction. There continues to be a debate in the science education world about the roles of explicit or direct instruction and discovery learning, often under various labels (Duit et al., 2001; Swaak, deJong, & van Joolingen, 2004). Over the years, a division has emerged between those who advocate for guided or direct instruction and those who advocate for unguided or discovery learning. The argument put forth in support of guided instruction is based on: (a) our knowledge of the limits of working memory and the importance of knowledge organized in long-term memory, as the goal of most instruction is to enable learners to store and retrieve information in a given situation; (b) the warrant that accurate mental representation of concepts requires complete and accurate information, not what a student may or may not misrepresent; and (c) empirical evidence for guided instruction (Kirschner, Sweller, &

Clark, 2006). Mayer (2004) points out that, regardless of the lack of supporting empirical evidence, “discovery has been replayed” about every decade (p. 18). Hmelo-Silver, Duncan, & Chinn (2007) agree “there is little evidence to suggest that unguided and experientially-based approaches foster learning” (p. 100). Other researchers have shown that explicit instruction can be efficient, effective, and engaging for students (Coll, 2006; Hudson, Miller, & Butler, 2006; Knight, 2002; Spada & Tomita, 2010).

Specifically studying analogies, Harrison and Treagust (2000) found that structured and scaffolded instruction about mental models helped students acquire accurate visualizations when teachers taught specific strategies and skills and provided time for critiquing the analogies and models. Other researchers, too, have called for guided instruction about the strategies involved with analogy used (Klauer, 1989; Thagard, 1992; Zook, 1993). Guided instruction has been found helpful for other strategies. Nussbaum, Sinatra, and Poliquin (2008) were able to show the effectiveness of teaching about the structure and nature of scientific arguments before students engaged in scientific argumentation. I suggest that teaching about the nature and use of analogies may be a similarly beneficial strategy for helping students use these tools effectively.

Scaffolds. In science education, strategies used in guided instruction are often referred to as scaffolding. As Losh and Nzekwe (2011) point out, it is assumed teachers will provide scaffolds for students. The term “scaffolding” was originally used in the study of language acquisition in infants (Woods, Bruner, & Ross, 1976), and the construct gained popularity during a time when Vygotsky’s work was influential. Currently, it refers to anything that is provided or enabled to allow students to accomplish something beyond their capacities. “Scaffold” can be a noun, referring to something

provided, or a verb, referring to a process or behavior. It can be informal and naturalistic, such as the interactions between mother and child, or formalized and strategic, such as learning materials or analogies (Pea, 2004).

Scaffolding is thought to be valuable for a number of reasons. One of the values of scaffolding is that it can provide models of how experts think and the strategies they use (Caliskan et al., 2010). Scaffolding may help decrease the cognitive load on working memory (Salden et al., 2009). It can help learners see the relevant components of the task, model strategies, and assist with mental representation of concepts (Davis & Miyake, 2004), as well as direct attention where it is needed (Duit, 1991). This may be especially helpful in conjunction with textbooks, which usually provide analogies but assume the learner has the skills for using them (Thiele & Treagust, 1994; Thiele et al., 1995; Venville & Treagust, 1997).

Examples of scaffolds. Scaffolds can be as simple as hints and cognitive prompts or as complex as diagrammatic representations and computer programs that help students organize and visualize their thinking (Bell & Linn, 2000; Sinatra & Chinn, 2011). Scaffolding can consist of guidance, challenging students towards deeper thinking, modeling, coaching, and questioning (Hmelo-Silver et al., 2007). Scaffolds tend to fall into two categories, “channeling and focusing” or “modeling” (Pea, 2004, p. 432). Teachers can provide hints that help students narrow down where information can be found. Often, students are encouraged to use a heuristic or note-taking system as a scaffold; the notes become hints or organizational tools for information. Textbooks, too, often provide scaffolds that channel and focus attention. They are often organized with headings, bold type, guiding questions, and definitions to help students use the tool

effectively. Teachers model procedures, safety practices, and study skills, as they teach, fading out the guidance over time to promote self-regulation and student growth.

Analogies can actually serve as the scaffolds for learning (Chiu & Lin, 2005; Holyoak, 2005). Science education and professional science contexts are filled with analogy use (Oliva et al., 2007; Treagust, 2007; Valle & Callanan, 2006). The research on the effectiveness of analogies used for learning should inform the use of these scaffolds.

Previous Research on Analogy Use for Learning

From a cognitive orientation, there is a great deal of useful research on the effectiveness of analogies for instruction. Three types of research helped shape the current research project. First, qualitative or observational studies provide evidence of the frequent use of analogies in science education and describe the wide variety of ways in which they are used. Second, there is qualitative evidence that learning or conceptual change can be related to analogy use. Finally, some classroom models for analogy use have been suggested in the literature.

Qualitative or Observational Studies

Of the wide variety of observational studies, those described here provide evidence of how analogies seem to be used naturally and intuitively. Observational studies also provide a glimpse into differences between novices and experts using analogies and how classroom use varies culturally.

Analogy Use in Classrooms.

Students. Much as in the museum study of parents interacting with their children (Valle & Callanan, 2006), described above in the section on naturalistic analogies,

students in classrooms naturally use analogies. Paatz et al. (2004) did a detailed study of student learning during extended instruction with analogies. By detailing the interactions of 16-year-old German students, they found that students enjoyed using analogies. Focusing on a particular student with interviews, they documented her movement over time towards more scientific vocabulary and her natural use of higher order relationships over physical features. They found evidence of inferencing between source and target. They also found, however, that their focus student carried some misconceptions to the target and that not all of her classmates used the same strategies during the series of analogies.

Teachers. Other observational studies inform us that teachers may not understand analogies well or carefully plan their use. Over the course of 40 lessons, seven high school science teachers were observed and then interviewed. The teachers thought they had used analogies more frequently than they actually did and had trouble distinguishing analogies from examples (Treagust, Duit, Joslin, & Lindauer, 1992). In a followup study of four Australian chemistry teachers, Thiele and Treagust (1994) looked for evidence of why teacher chose analogies, where they chose them from, and the characteristics of those analogies. The researchers identified seven themes that emerged from the observations:

1. Analogies were used most often when teachers thought students did not understand an explanation because the students asked questions, responded to the teacher incorrectly, or otherwise indicated misunderstanding.

2. Analogies were seldom planned by the teachers and were used spontaneously. Each teacher described a personal mental collection from which analogies were retrieved in response to student needs.
3. Analogies came from the teachers' experiences and professional reading. They seldom elaborated on the textbook-supplied analogies. Even in many instances when student experiences could have been used, teachers used their own experiences.
4. Analogies were often supplemented with diagrams or pictures, drawn by the teachers. One teacher mentioned that this actually helped her describe what she was picturing.
5. Mapping from source to target varied. When analogies were simple and not elaborated upon, there was little mapping. When analogies were more complex, usually one feature was mapped. If teachers felt there were several concepts that could be drawn from the source, they mapped more.
6. Teachers wanted to ensure that students understood the source. However, there were many instances when the teachers thought the students understood the sources and they did not.
7. There were few instances of the teachers pointing out where the analogies broke down.

In a widely referenced study of science teacher use of analogies, Dagher (1995a) found that teachers used analogies to "humanize science" (p. 260), clarify explanations, develop concepts, and communicate information. She found teacher use to be diverse and idiosyncratic; teachers drew on their own values and judgments of student interest. Like

Thiele and Treagust (1994), she found that students may not have understood what was intended by some of the analogies.

In a more recent literature review of classroom analogy use, Oliva et al. (2007) found few studies documenting teachers planning the use of analogies and a few studies on the placement of analogies and one on the roles of students and teachers. They questioned teachers and found large discrepancies between how the teachers thought analogies should be presented and how they reported presenting analogies.

These observational studies are representative of the literature and provide evidence that neither teachers nor students often approach analogy use strategically. Both students and teachers tend to use analogies spontaneously and without much planning for how these tools could promote learning. In fact Thiele and Treagust (1994) suggested that teachers are not familiar with the power of using analogies, as evidenced by their disregard for valuing one analogy over another. These studies found that analogies are seldom chosen in advance of instruction. The teachers did not consider any documented effectiveness for their analogies or base their choices on pedagogical principles or even on scientific soundness.

Experts and novices. Evidence for steps or a progression during analogy use comes from studies of experts and novices using analogies. Clement (1988) identified four processes within analogy use, as he observed scientifically trained experts faced with an unfamiliar problem. He followed up (1998) by documenting the similarities in how experts and novices approach using analogies. Even though he did not provide sources, he found that both experts and high school students naturally used analogical reasoning. Both groups went through a similar process of choosing a source (although the experts

chose more helpful sources), matching the key relationships, and transferring information from sources to targets, often through a series of bridging analogies.

Working with much younger children, Mayer, Hammer, and Roy (2006) observed how even the young students followed much the same pattern. They found that the children tried and discarded several analogies as they built explanations, tested them, and adjusted them in response to critiques from peers.

Cultural differences. One pertinent series of observations about analogy use was done using the Trends in Mathematics and Science Study (TIMSS) videotapes (Richland et al., 2004; Richland & McDonough, 2010; Richland et al., 2007). Classroom lessons were videotaped for a purposeful sample of eighth-grade mathematics and science lessons in the United States, Australia, the Czech Republic, Hong Kong SAR, Japan, the Netherlands, and Switzerland. Other than the U.S., the other countries were chosen because their students were consistently top performers on international tests.

In the first analysis, which was of mathematics classrooms, Richland et al. (2004) found several consistent differences among the classrooms. First, verbal analogies were used more frequently in American classrooms than in the higher performing classrooms. Second, very few instances of students mapping the source to the target were found in the American classrooms.

Richland et al. (2007) focused on how analogies were used in American, Hong Kong SAR, and Japanese mathematics classrooms. They specifically looked for, among other characteristics, explicit mapping of information from a known source to an unknown target and alignment and mapping strategies. They found that Asian teachers used more spatial supports and gestures and gave more prompts for mental

representations than did American teachers. The researchers hypothesized that the lack of scaffolding cues, such as gestures and prompts, in American classrooms may lead to uncertainty about what the students are actually visualizing and encoding into memory.

Lessons Learned from Qualitative Studies. For the current research study, these qualitative studies provide three key findings. First of all, analogies are usually used in classrooms without planning or pedagogical focus. Second, analogy use follows a progression or series of steps on the part of the learner. Third, teachers were seldom observed helping students follow a progression or assisting with mapping the sources to the targets.

Analogies in Textbooks

The natural tendency in science classrooms would be to expect that science textbooks would provide analogies to help students learn concepts. Textbooks, however, are surprising sparse in some aspects of analogy use that could help students.

Curtis and Reigeluth (1984) analyzed 26 science textbooks, elementary to post-secondary, that were published between 1963 and 1983. They found that science textbooks provided no instructions for analogy use. Most analogies used a concrete base and an abstract target and were embedded within the context of the explanation. While many of the analogies included some relational mapping help, most were text-based and few had visual aids. With 49% of the analogies, there was no attempt to ensure the sources were understood by the learners.

Glynn et al. (1989) found that high school and physics textbooks had more elaborately developed analogies. Textbooks for both older students (college) and for younger students tended to provide just very brief analogical statements for concepts.

Analyzing 43 textbooks, they found no mention of how analogies could be used in any of the textbook introductions, either in the teacher or student editions. They suggested that, if the textbooks were not going to discuss how analogies work, teachers have a responsibility to fill that role.

Iding (1997) proposed that textbook publishers and authors must think that analogies are effective instructional tools because of the frequency of their appearance in written materials. While this belief is “intuitively compelling” (p. 234), she found little development of analogies in the materials or assistance with their use, for either teachers or students.

Chemistry, biology, and physics textbooks used in Australia have been examined (Thiele & Treagust, 1994; Thiele et al., 1995; Venville & Treagust, 1997). Most of the analogies were presented without any assistance for mapping or assuring that the source was understood. In tandem, they interviewed textbook authors. The authors clearly understood the value of analogies but were reluctant to elaborate on analogies in print because they thought it needed to be done in the classroom, where analogies could be tailored to the reactions of the students. The textbook authors expected that teachers would provide instruction on strategies for using analogies.

Newton (2003) replicated Curtis and Reigeluth’s (1984) analysis with 80 elementary expository science books, rather than textbooks. She found fewer analogies, which tended to emphasize the structural features rather than underlying concepts. More illustrations were used with books for younger children. None provided information on how to use the analogies. College textbooks, specifically biochemistry textbooks, also provide analogies (Orgill & Bodner, 2006). However, even though textbooks are so

important to college students, strategies for using analogies were not provided, nor were many of the analogies detailed enough to help students with mapping.

Lessons Learned from Textbook Analysis. Textbooks cannot be relied on to provide strategies for using analogies effectively. Very few instances have been found where the analogies are explicitly mapped. Textbooks provide analogies, but the teacher needs to provide contexts and strategies for using analogies.

Quantitative Studies

Because analogies have been studied so intensely for such a long time, there is a plethora of quantitative studies about their usefulness. The hurdle is that each researcher chose a different outcome as a measure of effectiveness. For the current research project, I will summarize findings from those that studied the effectiveness of analogies for science learning, those that examined the importance of mapping, and studies about bridging analogies.

Analogy vs. no analogy. The classic design of studies on the effectiveness of analogies is a comparison between an analogy condition and a no-analogy condition. This has been done across a wide age spectrum. However, as several researchers have pointed out, there is not always consistency in what is labeled and tested as an analogy (Dagher et al.,1993; Glynn et al., 1989; Oliva et al., 2007; Pramling, 2009). It is also clear that the outcomes measured are very different for each study, making generalizations difficult.

With and without analogies for young children. One of the classic studies of the effect of analogy use on learning was done by Newton and Newton (1995). They studied six- and seven-year-olds learning about electric currents. In the analogy condition,

children saw an analogous demonstration using a pump soap dispenser filled with water. Students were then interviewed as they built a circuit with a battery and small light bulb.

In this study, the children were not told that the pump was like an electric circuit. Yet the analogy condition group was better able to give reasons for the circuit they built. Almost half of the analogy condition group spontaneously referred to the pump demonstration in their explanations.

Conceptual change. Chiu and Lin (2005) studied a variety of analogy conditions to determine if different conditions led to ontological shift, as described by Chi et al. (1994). They used no analogies, single analogies, similar analogies (two sources providing the same features), and complementary analogies (two sources providing different features). When 10-year-old students were given post-tests and interviewed, the researchers found that the group provided with complementary analogies showed statistically significant ontological shifts in predicate use.

Unfortunately, no previous work on complementary or similar analogies was cited. The findings about ontological shift would have been more powerful if specific evidence for a distinction between the types of analogies was documented. This study, though, does represent another outcome researchers use to measure learning with analogies.

Text-based. Fourth- and sixth-grade students were provided with either a text-based analogy or a text with no analogy (Yanowitz, 2001). The paragraphs were adjusted so that the length was not a variable. Each participant was tested immediately after reading.

In this study, the researcher was interested in measuring performance on questions requiring inferences. There was no significant difference in recall between the analogy and control groups. However, the students in the analogy group answered significantly more inferential questions correctly than did the control group students, and the sixth-graders answered more inferential questions than did the fourth-graders.

In a follow-up experiment, the non-analogy paragraphs were stripped of extraneous details and the paragraphs were read aloud by the teacher, rather than read by the students. The shorter paragraphs for the control or no-analogy group were read twice by the teachers. Again those in the analogy condition scored significantly better on the inferential questions. This study points out the importance of measuring more than recall when studying analogy effectiveness. It also provides evidence that repetition of information is not an equivalent elaboration strategy when compared with analogy use.

Multimedia. In another recent study, researchers varied the amount of multimedia used in electrical circuit instruction with water flow analogies (Zheng et al., 2008). They measured both recall and transfer and found that analogies using multimedia were the most effective for fourth-graders. These researchers explained this as the result of schematic networks being activated by multimedia and less complex networks being activated by text-based analogies.

Lessons learned from evaluating analogy use. This sample of studies comparing analogy conditions and no-analogy conditions demonstrates the wide variety of outcomes measured in studies. The outcomes being studied dictate the design and what is controlled. It is also important to note that, in no studies were all of the children using analogies more successful than those not using analogies. In all of them, some students

not using analogies were also successful when outcomes were measured. Unfortunately, in none of these studies was effect sizes reported.

Scaffolding with analogies. There are few empirical studies that address strategies for using analogies. This section summarizes representative studies in which analogy use was combined with helping students understand analogy use, specifically the process of mapping.

Cued alignment. To test the hypothesis that American teachers need to assist students by providing alignment cues during analogy use, Richland and McDonough (2010) compared undergraduate student outcomes from "highly supported" analogy use with student outcomes from "minimally supported" analogy use (p. 30). The highly supported analogies, in videotaped instruction, provided support for noticing the alignment between source and target. On a post-test, the cued group had significantly higher scores than the minimally supported group when the source and target were very different. A follow-up study reported by the same authors found that undergraduate students who were cued had statistically stronger scores on both a post-test and a delayed post-test.

Extensive scaffolding. With much younger children, Flick (1991) studied an extensive unit on states of matter. Third-, fourth-, and fifth-grade students moved through 30-minute lessons each day for two weeks. In the lessons, a collaborative class diagram was developed, showing the characteristics of a sugar cube as it was crushed into chunks, powder, and dust. The students then labeled the parts of the diagram to correspond with states of water.

On pre-test and post-tests, Flick analyzed the student answers for operational descriptions or those using terms from one domain (sugar) to explain another (water). The increase in these analogous descriptions from pre- to post-test was statistically significant.

Justifying similarity ratings. Mason (2004) worked with eighth-grade students to see if they could not only rate similarities between two scenarios, but if they could justify their ratings. She found that, unlike the Kurtz et al. (2001) study done with adults, younger students gained the most when they were asked to list the commonalities between the scenarios. She suggested that active comparison provided an opportunity for seeing the underlying structure. It appears that active comparison served the purpose of an elaboration strategy.

Writing about the mapping. Klein et al. (2007) used a variety of assignments to have undergraduate students map a source to a target. One group wrote about the analogy, one group verbally described the analogy, and one group did a think aloud while writing about the analogy. They were interested in the load on working memory that each of these tasks would impose on learning the science concepts.

Students with low working memory spans scored higher in the writing and think aloud plus writing conditions than in the speaking condition; there were no statistically significant differences among the higher working memory students. Regardless of working memory span, students in the writing conditions used more third-order relationships, which mapped causal relationships, than did students in the speaking condition. When a sequential analysis was done of the steps used by the students, it was

found that writers explicitly mapped explanations from the source to the target while speakers did not, even if they were able to understand the concept.

Working memory limits. In another study of the load on working memory, Tohill and Holyoak (2000) studied how taxing working memory would affect analogy use. They hypothesized that aligning relationships takes more working memory capacity than mapping surface features. They randomly assigned university students to an induced anxiety group and a non-anxiety group. Both groups were given a pair of line drawings on a computer screen. An object was identified in the first drawing and subjects were to identify an analogous object in the other drawing. The pairs of pictures were cross-mapped, so underlying relationships, rather than surface features, were needed to find the analogous objects. As they hypothesized, the induced anxiety group was less likely to pair based on underlying relationships, even when the experiment was repeated with instructions to find pairs based on relationships.

Learning is constrained by limited working memory. Elaboration allows a learner to connect and activate existing schema and to chunk information (Chi, 2000; Nussbaum, 2008). The mapping or alignment in an analogy provides elaboration to foster learning.

Mapping guidance. Blake's (2004) study of 9- through 11-year-olds provides further evidence of the value of guidance for mapping. He measured use of non-scientific, proto-scientific, or scientific explanations after children were taught with an analogy or not. The analogy condition group was given instruction about analogies. The source (aluminum can recycling) and target (rock cycle) were specific mapped with the children, one feature at a time. Concept maps were analyzed for explanations. There was

a statistically significant advantage for those in the analogy group. They also used their new knowledge with greater accuracy than the control group did.

The gains made were movements from non-scientific to proto-scientific explanations, rather than leaps from non-scientific to scientific. They also noted that not all children in the analogy group made gains and that some children in the control group made gains.

Persistence of strategies. Tunteler and Resing (2007) studied whether strategies for using analogies learned by young children (ages five through seven) would persist over time. Group one was given assistance in the form of a story problem that was analyzed and then, feature by feature, compared to a second story problem. For six weeks, this group repeated this procedure each week. A second group also did this activity weekly, but without the initial training. A third group did the activity, without training, at week one and four. A fourth group was given only the target story problem each week. All were scored on whether they used an analogy for solving and whether they verbalized using an analogy. The researchers concluded that the initial training fostered spontaneous use of analogies over time and that this was more pronounced for older children. The importance of this study is that it demonstrated that strategies taught to children were not only worthwhile but persistent.

Less successful analogy use. One of the most frequently cited studies of the effectiveness of analogies was done by Duit et al. (2001). They used student discourse as a measurement of conceptual change, as students changed from natural, colloquial language to gradually more appropriate scientific language. They were not specifically

trying to show an effect of analogy use, but were trying to relate the role of analogies in learning to what students said.

In this German, 10th-grade physics class, the students worked collaboratively on a series of analogies to help them understand chaotic systems. They found that students needed a great deal of assistance in aligning the sources and targets because they often struggled with determining which features to map or focused on surface similarities. This study was done in the context of a very complex concept, one few of us understand well. The value, though, was in documenting how student interpreted the analogy and how much scaffolding they needed. The researchers concluded that analogies can lead to both learning and misconceptions; therefore, students need "substantial guidance" in using analogies, especially for complex concepts (p. 30).

Lessons learned from scaffolding with analogies. Each of these studies used assistance for the learners in using analogies, either through teaching them how to use analogies or by providing a structure that required students to explicitly map. Taken together, they provide evidence that mapping is difficult and transfer of accurate scientific information cannot be taken for granted. They also provide evidence that structures providing elaboration during the mapping process are beneficial, and that persistent strategies can be taught. However, in all of these studies, not all students benefitted the same way. Analogies are effective in different ways for different students.

Classroom Models

Research Base for Classroom Models

With all that has been researched about analogies in classrooms, there are surprisingly few studies of how teachers can effectively present and use analogies with

students. This section presents information on what should be the basis for a classroom model and the classroom models that have been proposed by researchers.

Useful classroom models of instructional analogy use should be aligned with what is known about how analogies work and learning theory. Fortunately, over the last 40 years, a theoretical model has been developed and tested to specifically explain mapping, the focus of the current study.

Mapping for transfer. A good theory for mapping would allow prediction of the transfers, explain how the mapping happens, account for how it is constrained, and be based on evidence for these explanations. The source and target components of an analogy can be mapped, or aligned, based on either surface features (such as shape, size, color, etc.) or relationships (such as cause and effect), which are also known as the structure. The value of an analogy is in identifying the underlying structure or principle that is common to both the source and target. If a learner maps the features of a source onto the target, little would be transferred about the principles or concepts underlying the target. The source would simply be a description of the target. Unless the underlying structure and relationships of the features is mapped, inferences cannot be made in order to build and organize knowledge of the target. The important point is that information is mapped from source to target through a system of relationships, regardless of whether or not the objects themselves are very similar.

Structure mapping. Most of the research literature relies on Gentner's structure-mapping theory to explain mapping for transfer. According to this theory, relationships are mapped rather than features, and there is a one-to-one, parallel correspondence of source and target features and their relationships. The systematicity principle explains

how mapping is constrained (Gentner, 1983; 1988; 1989; Gentner & Markman, 1997; Gentner & Toupin, 1986; Markman, 1997).

Relationships. Any description of analogical mapping has to account for the inhibition of matching appearances and the promotion of choosing relational structures. Both the source and target have attributes or components, some of which are features and some of which are predicates that indicate relationships. An often-cited depiction of this distinction is given by Gentner and Toupin (1986). If the source and target both have features that are red, that is an attribute match and could be notated as

$$[\text{Red } (b_i)] \rightarrow [\text{Red } (t_i)].$$

Note that Gentner and Toupin use the term "base," distinguished by the "b," rather than "source." Their next example, of a structural match, uses the relationship between two attributes of the source, b_i and b_j and the relationship between two attributes of the target, t_i and t_j:

$$[\text{Collide } (b_i, b_j)] \rightarrow [\text{Collide } (t_i, t_j)].$$

In other words, the relationship between b_i and b_j is that they collide. The relationship between t_i and t_j is also one of collision. This makes the source and target analogous because they have the same relationship between features. The arrow indicates that the relationship between the source attributes becomes an inference that transfers to the relationship between the target attributes.

Feature attributes can be singular. In contrast, relational predicates need a pairing or an argument (Gentner, 1983). To understand this, think of a causal situation. There is no causation if there is only one feature or object attribute. Any relationship requires more than one feature, attribute, or component.

Over the years, a great deal of evidence has been gathered for human preference for comparing relationships over features (Holyoak, 2005). In naturalistic settings, people tend to compare relationships rather than features (Dunbar, 2001). Adults tend to interpret analogies relationally, when they could be either relational or featural, and judge the aptness of metaphors and analogies higher if there are relational interpretations. (Gentner, 1988). In one set of studies, adults were tasked with determining whether or not two sentences were analogous. The researchers changed the verbs to change the relationships and the nouns to change the surface features. The researchers also tracked the response time. As predicted by structural mapping theory, the subjects consistently rated relationally similar sentences as more analogous than featurally similar sentences. They also found that, when the relationships were similar but not synonymous, the processing time was longer (Gentner & Kurtz, 2006). In another study, people were given pairs of stories. The stories were remembered on the basis of surface similarities. However, when the subjects were asked to use one story to make inferences about the other, they used the structural similarities or relationships (Gentner et al., 1993).

In another study, each participant was given pairs of sentences and asked to justify whether or not the pairs were analogous. Sometimes the subjects rejected a pair because the same verbs took on different meanings when paired with different objects. An example that came to my mind was the different meaning of a sentence about kicking a soccer ball compared to a sentence about kicking a dog. The researchers concluded they had evidence for the importance of relational structure (Gentner & Kurtz, 2006).

One-to-one correspondence. Attributes of the source are mapped in a one-to-one correspondence with features of the target, based on their roles. In other words, a

relationship in the source is mapped only to a single relationship in the target. This bidirectional parallelism is known as isomorphism, and it is critical to shaping the analogy (Klauer, 1989; Markman, 1997). It follows logically that the matched relationships will have matched arguments (Gentner & Markman, 1997; Markman, 1997). For example, if the relationship in the source is [Tug (b_1,b_2], the mapped relationship in the target is inferred to be [Tug (t_1,t_2)] or even [Move (t_1,t_2)], not a completely different relationship, such as [Create (t_1,t_2)]. Relationships can also be parallel because of the differences, because analogies use simultaneous, not hierarchical instances (Mason, 2004). The example that Bill is a boy and Margo is a girl is aligned, through the commonality of gender. However, that Margo is tall and Bill is happy is not parallel or aligned.

Systematicity principle. Systems of relationships are preferred over isolated relationships and higher order and more complex relationships are used over simple relationships (Gentner, 1983; Gentner & Toupin, 1986; Markman, 1997). If predicates belong to a system of relationships, they are more likely to be mapped with the target. Meaning is built because networks of relationships are mapped over isolated pairs of features. There are many combinations of possible mappings between a source and target; the systematicity principle actually puts constraints on all the possible relationships that could be mapped (Gentner, 1988; 1989; Gentner et al., 2001; Gentner & Markman, 1997).

Predicting. Structure-mapping theory, which describes the importance of underlying structure, one-to-one correspondence and the systematicity principle, allows accurate prediction of which predicates will be mapped by considering the underlying

relationships. This is really important for science educators, as they are scaffolding development of scientific mental models. I will use the ubiquitous cell-nucleus-is-like-the-mayor analogy as an example. When students map the pairing, the physical features are disregarded in deference to the roles or underlying structures (primacy of relationships). The functions a mayor performs are mapped, one-to-one, to the functions a nucleus performs (parallel, one-to-one mappings). Because the mayor's roles are part of a system of relationships with other components of the town, those predicates are used over isolated predicates (systematicity principle).

Mental models. Concept building, specifically in science education, requires understanding the development of mental models (Vosniadou, 1989). Structure mapping theory provides the basis for how these models are constructed, but leaves open questions about misconceptions. Students tend to take a source literally, rather than as a model for the target. I propose that students need to be able to identify where the mapping breaks down in order to combat this.

Models

It is important to know, first of all, whether teachers do actually provide or plan steps for helping students use analogies. Richland et al. (2004) analyzed TIMMS videotapes from American eighth-grade mathematics classrooms. They looked for instances in which the base and target were specifically mapped in the classrooms. Teachers "produced hints towards mappings" (p. 48) in most lessons that had analogies. After analyzing, they suggested that "if the teacher is producing a large number of the analogies, it is unknown whether students are understanding the structural mapping underlying the analogy or are simply waiting for the teachers' interpretation" (p. 55).

Their research led them to suggest that students may be more likely to understand analogies in which there is explicit mapping.

Again using the TIMMS video bank, Richland, Zur, and Holyoak (2007) followed up with a comparison of analogy use in Hong Kong, Japan, and the United States. They found that the Asian teachers "provided more support for learning from analogies than did the U.S. teachers" (p. 29). Asian teachers did this by using cuing scaffolds, such as keeping the base visible while pointing out alignment between the base and target. A strategy such as this may not only reduce demands on working memory but may draw attention to the comparison.

These observations were done in mathematics classrooms, not science. However, other researchers have also proposed that there is value in having steps or strategies for using analogies in classrooms (Clement, 1993; 1998; Glynn, 1991; Treagust, Harrison, & Venville, 1998; Zeitoun, 1984). Unfortunately, the classroom models available to teachers are generally lacking in empirical evidence about their components and are devoid of theoretical underpinnings.

A myriad of observational studies of classrooms have provided examples of the components of structure mapping theory. In contrast, there are four classroom pedagogical models that have been developed. In this case, I am using the term "model" specifically for a systematic set of strategies purported to help students learn from analogies. As Treagust, Harrison, and Venville point out, teachers are seldom trained in the use of analogies and their dangers, so "a carefully planned pedagogy is required" (1998, p. 87). Other researchers have also decried the lack of research connecting studies of analogies with research on teaching models (Oliva et al., 2007).

GMAT. One of the earliest models for classroom use of analogies was the General Model of Analogy Teaching or GMAT (Zeitoun, 1984). Based on his review of what was known about analogies and their limitations related to learning, Zeitoun proposed nine steps to use when teaching with analogies. None of these steps are specific to what students do; all focus on the teacher actions and preparation: (a) determine if the students understand analogical learning; (b) assess students' prior knowledge about the target; (c) analyze what the students need to learn about the target; (d) evaluate the analogy for appropriateness to the target and determine whether it will be easily taught and understood; (e) look at what resources will be needed for using the analogy; (f) decide on a teaching strategy and the context; (g) guide students through the analogy; (h) evaluate the success; and i) revise.

This model is often referenced by other researchers; however, I was not able to find quantitative studies that attempted to validate this model. Much of this model is simply good teaching practice, rather than being specific to using analogies, so bits and pieces have been validated in educational research. Steps three, four, and seven, though, are specific to using analogies and could promote effective analogy use in classrooms.

TWA. The Teaching With Analogies (TWA) model was developed to outline the steps that should be used when teaching with an analogy (Glynn, 1991; Glynn et al., 1989). Nineteen high school science textbooks were reviewed and effective analogies in them were identified (Glynn et al., 1989). The value of analogy is a function of its goal; in this case, instruction was the goal, and three criteria were used: (a) the number of features to compare; (b) the similarity of the features; and (c) the conceptual significance of that comparison (see p. 386). The determination of analogy effectiveness, however,

was made from a pedagogical viewpoint, with no measure of actual student learning; analogies that followed a pattern of good instructional practice were considered effective. Once the exemplary analogies were identified, six steps were identified for the TWA model. These start with introducing the target concept, then recalling a source concept. Next the similar features of the two concepts are identified and mapped. From that mapping, conclusions about the concepts are drawn. Finally, where the analogy breaks down should be noted. They suggested that this model would be helpful in teaching students to "interpret, criticize, and extend an author's analogy" (Glynn et al.,1989, p. 390). Authors and teachers could also consider this model as they choose and present analogies.

Studies of TWA. Use of the TWA model is often described qualitatively (Glynn, 2007; 2008). A typical example is the description of a teacher's script during a science lesson (2008). The script for the introduction to the lesson was provided. As a qualitative description, however, it was weak, perhaps because it was intended for a practitioner audience. There were no efforts to describe how the teacher chose the analogy, if she did. Apparently the students were listening to a lecture, which included a diagram comparing Coulomb's law with Newton's law of gravitational force. No description of what the students did was given, nor was there any indication that the teacher checked for understanding, either by asking or answering any questions. The reader had no context for the observation or even any idea of whether there was an observation or if the teacher supplied the script. In another example, Glynn provides a description of how TWA should be used with a "fictitious conversation" rather than an actual observation (1991, p. 234-237).

As an isolated example, this description of Glynn's TWA model is not alarming. However, for a "research-based model" (Glynn, 2008, p. 113), it is very difficult to find research that shows its effective use in classrooms. The TWA model was developed from analysis of textbooks and Glynn has called for empirical studies to validate the model (Glynn, 1991). In a personal communication requesting information on validation of the TWA model (October 20, 2010), Dr. Glynn pointed me towards a practitioner-focused article in *Science and Children* (Glynn, 2007), an article on considerations for web-based instructional strategies (Glynn et al., 2007), and two studies on the effectiveness of textbook analogies (Glynn & Takahashi, 1998; Paris & Glynn, 2004).

Glynn and Takahashi (1998) studied middle school students using textbook analogies that had both a text and a graphic component, what they termed "elaborate" analogies (p. 1130). Their operational definition for "elaborate analogy" has three components: systematic mapping, activation of verbal and visual process, and the interaction between the mapping and processes. No background information on or reference to cognitive processes was used. The analogy between a factory and an animal cell was constructed according to TWA model guidelines.

Eighth-grade students (N = 58, ages 12 to 14 years old) were randomly assigned into either the experimental treatment group or the control group. The experimental group read a text that had the factory/cell analogy at the beginning, accompanied by a line drawing of workers in a factory, labeled as the parts of a cell. The control group read a description of each component of the cell and its function (no analogy). There was no group that used an analogy that was not constructed by TWA guidelines. There was a between-subjects variable of the text type and a within-subjects variable of retention

interval when students were tested on recall by having to describe what each cell part does. For each cell component, the answer was either correct or incorrect when scored. After the recall test, students were also asked whether the cell components and their functions reminded them of anything similar, and they wrote out their answers.

The students using the analogy-enhanced text had higher recall scores, $F(1,56) = 7.96$, $p = .007$, $MSE = 4.44$. The recall scores did not differ significantly, nor was there a statistically significant interaction effect.

The experiment was then replicated with sixth-grade students ($N = 32$, ages 10 to 12 years old), again with only two groups, no analogies or TWA-designed analogies, and a recognition test was given in addition to the recall test and the reminder question.

At three points in time, before the intervention, right after the intervention, and after two weeks, students were also asked to rate the target (cell components and their functions) on a questionnaire as to being important, interesting, and understandable.

Analyses were done the same as in the first experiment, but analyses of covariance (ratings before the intervention as covariate) were used to determine the effects of the type of text and the two-week interval on interest, importance, and understandability ratings. For both the recall and recognition questions, the experimental group scores were significantly higher than control groups', $F(1,30) = 14.51$, $p < .001$ and $F(1,30) = 11.13$, $p = .002$ respectively. With these younger children, the immediate scores were significantly higher than the scores after a two-week interval, and the experimental group still scored significantly higher than the control group. The intervention group rated the concept as significantly more understandable than the control

group did. When the effect of the analogy was compared between sixth- and eighth-grade students, the analogy accounted for almost three times more variance.

These two experiments provided evidence that the effects of the TWA analogies were stronger for the younger students but beneficial at both age levels. Students' ability to remember the analogy was stable over the two-week interval and those using the analogy displayed more depth in their answers. The analogy used included statements about where the analogy did not align and broke down. However, students were not given instruction on what an analogy is or strategies for using analogies to learn. This study was limited to text-based instruction; there were no student-to-student interactions or interactions with the teacher.

Paris and Glynn (2004) studied elaborate analogies in science texts used by adult pre-service teachers. In this study, there were three levels of analogies: no analogy (control), simple analogy, and elaborate analogy. In their operational definitions, a simple analogy is a statement, with no details, explanations, or mapping cues. They defined an elaborate analogy as it was described above (Glynn & Takahashi, 1998), hypothesizing that it provided instructional scaffolding. In this study, three different analogies were used. A factory was used as an analogy source for an animal cell, an electric current was compared to water flowing through pipes, and the human eye was analogous to a camera. Each analogy was built using the guidelines of the TWA model and each contained a labeled diagram of the source showing the alignment with the target. A labeled diagram of the target concept or object was included in both the no analogy text and the simple analogy text.

All subjects (*N* = 140) read and studied three passages, one for each concept or object. Each subject read about one concept with no analogy, another concept with a simple analogy, and another concept with an elaborate analogy, in random order. After studying the three texts, each participant answered nine questions, three questions for each concept, about their interest, understanding, and ability to explain the concept. They then ranked the passages as interesting, helpful for understanding, and helpful for explaining to others. Finally, they were tested with a series of questions, scored as acceptable or unacceptable, designed to assess retention of information, ability to make inferences about the information, and metacognitive awareness or confidence about giving the correct answer. Just over half of the participants were also interviewed and asked to explain their text rankings.

For all three concepts, ratings (interest, helpful for understanding, and helpful for explaining) were significantly higher for the elaborate analogy texts than either the no analogy or simple analogy texts, which were not different statistically. Participants found the text more interesting, more helpful for understanding the concept, and more helpful if they were to explain the concept to others in the elaborate analogy conditions. Retention of information was significantly higher, inference-making was better, and subjects were best at self-evaluation in the elaborate analogy text conditions, and there were no statistically significant differences between the no analogy and the simple analogy conditions.

The researchers concluded that elaborate analogies, which, according to their operational definition, include text and graphics, specify the alignment between source and target, indicate where the analogy breaks down, and provide conclusions that can be

drawn from the analogy, were effective in retention of knowledge because the analogy provided instructional scaffolding, greater imagery, and the advantage of tapping into existing conceptual networks. Participants were better able to judge their own understanding of the concepts and found them more engaging. This research design did not isolate which components of the elaborate analogies may have been helpful. It could have been the TWA steps. It could have been the combination of text and graphics. Or it could have been a combination of the elements.

Usefulness of TWA. The value of the TWA model is in its specific steps, which have potential to help teachers and/or students work through the analogical reasoning process. The process does not need to be linear; many teachers, for example, use pedagogical models in which the target concept is not identified at the beginning of the lesson cycle. The second listed step may give the impression that students must recall or retrieve their own source. This does not make sense if they do not know what the target is or understand the target, for they have no criteria for an appropriate source. Instead, with instructional analogies, the source is provided by the teacher and should be carefully chosen to activate students' prior knowledge.

The TWA model is an intuitively useful model. However, it was developed on a very subjective definition of what makes an effective analogy and through the examination of textbooks, not even classroom observations. No references to specific learning theories or models were given (Glynn, 1991; 1996; 2007; 2008; Glynn et al., 1989; Glynn & Taasoobshirazi, & Fowler, 2007; Glynn & Takahashi, 1998; Paris & Glynn, 2004). It is difficult to judge the value of an intervention without a theoretical basis. I am reminded of Stephen Hawking's statement about the importance of having a

theory to explain the mechanisms, as our understandings are “conditioned by the theory to which we subscribe” (1993, p. 43).

As mentioned previously, Glynn et al. (1989) gave three criteria for judging the value of an instructional analogy. Based on structure-mapping theory (Gentner, 1983; 1989) I would suggest different criteria for judging the value of an analogy. First of all, an analogy should be judged valuable if learning can be associated with it, qualitatively or quantitatively. Second, an analogy should be judged valuable if enough of the underlying relationships in the source and target can be aligned to make inferences about the target based on the source. After all, the alignment of the underlying relationships is what makes an analogy unique. While “number of features compared” and “similarity of the features compared” (Glynn et al., 1989, p. 386) may help in retrieving an analogical source to use, especially in problem solving, comparing the surface features may actually lead to misconceptions (Newton, 2003).

FAR. The FAR model (Focus, Action, Reflection) was developed by Australian researchers, Treagust, Harrison, and Venville (1998), while working with pre-service and in-service teachers. Research had shown that analogies sometimes led to misconceptions and little learning, and these researchers wanted a way to help science teachers use analogies more effectively. Over the course of several years, they worked with high school science teachers, using Glynn’s (1991) TWA model as a starting point.

After five experienced teachers used the TWA model in their classrooms, discussions were held about the successes and concerns. Teachers pointed out that the TWA model did not guide planning or reflection, two important aspects of teaching, thus

the “Focus, Action, Reflection” pattern was developed. This newer model was then used by six teachers and was adjusted slightly.

The FAR model is designed to give steps that the teacher should consider in using analogies in the classroom. Under the heading “Focus,” this model includes thinking about the concept to be taught, its difficulty level, abstractness, and what students may already know. At this point, the teacher should consider the source and whether it is a concept, event, or thing with which students will be familiar. During the “Action” sequence, the teacher guides students through the similarities and differences between the source and target, including where the analogy breaks down. Finally, in the “Reflection” portion, the teacher decides whether the analogy was useful and appropriate and what adjustments need to be made for future use.

Studies of FAR. When this model was used in classrooms, the teachers reported they felt more confident about using analogies, they took into consideration students’ existing knowledge, and they pinpointed how they would change the presentation for the future. The teachers thought that guiding students through the similarities and differences was useful to the students. Several brought up that their own weak content knowledge made some analogies very confusing. Several recommended that students be taught the value of analogies and trained to use them. The researchers then used the FAR model with final-year pre-service teachers in order to help them address known student misconceptions (Treagust et al., 1998; Treagust et al., 1996).

Over the years, this model has formed the basis for many case studies of analogy use, particularly by these authors, but seldom describing what teachers or students do

during each step. I was unable to find any studies of the model's effectiveness for students.

Usefulness of FAR. Like the TWA model described above, FAR is intuitively gratifying. However, it is not grounded in a theoretical base or even on well-known educational research of classroom practices. It is a very teacher-centered model, designed for and used by teachers. There is no quantitative evidence for its effectiveness as a strategy. Carefully controlled studies, isolating each of the steps of the model, could be conducted. At the very least, the FAR model should be aligned with other education research.

Bridging. A variation on classroom models of analogy use is bridging. It is very difficult for students to give up their naïve understandings, even with analogical demonstrations (Clement, 1998; Harrison & Treagust, 2000). In this model, students build their understandings, analogy by analogy, until they have overcome non-scientific explanations. Building on Minstrell's work (1982), Clement (1993) used a series of related analogies for the forces on an object at rest, starting with a very accessible, plausible source, and ending with the more abstract source. With each analogy, students transferred inferences from the source to the target, and in some cases, the target then became the source for a new target. Work with bridging analogies has shown that gradually providing analogies to adjust student understanding can help, as students come to accept each step towards canonical understanding (Clement & Steinberg, 2002).

Four case studies of tutoring sessions, two in which there was evidence of conceptual change and two in which there was not, identified factors that are important for the effective use of bridging analogies (Brown & Clement, 1989). Three students

working on four different physics misconceptions were tutored through an interview process. One student was a freshman in college; the other two were high school juniors.

The researchers (Brown & Clement, 1989) found, first of all, that the students started out thinking they understood the source. In the first case study, for example, with a book resting on a table, the student thought he understood, but did not accept that the table was exerting an upward force. In a traditional use of an analogy, an assumption would be made that students understand the source and could make inferences to the target from it. These case studies pointed out the inherent problem with that assumption. The second finding of importance was how resistant the students were to accepting more canonical explanations, even when they were faced with and accepted the evidence in the form of analogies. It was clear that students did not accept the examples as analogous. It should be noted that there was no attempt to specifically map or align the source and target.

Brown and Clement made a point that, in these case studies, "the analogies appeared to help *enrich* the students' conceptions of the target situations" (p. 256). In other words, an analogical source provides features, attributes, and causal relationships for the target. Another point worth mentioning is that bridging analogies do not force the student to accept the soundness of the analogical relationship. Instead, students move from one intermediate analogy to another, after they accept the soundness of the first. Bridging analogies may be particularly useful when a student does not see the source and target as analogous.

The factors that appeared to influence successful conceptual change were: (a) a source that is useful and accepted by the student; (b) explicit development of the

analogous relationship between the source and target through intermediate analogies; and (c) interaction between student and teachers in a process.

Brown and Clement set out to specifically address misconceptions, known to be very robust and difficult to dislodge. There may be a limited need for bridging analogies, especially in situations where students do not have firmly entrenched misconceptions about the target. More traditional forms of instructional analogies may be adequate for building new explanatory models about the target. It should also be noted that it would be very, very difficult to develop sound analogy bridges for the myriad of target concepts that could benefit from being taught through analogies. At least some of the actual value of bridging analogies may come from the intense interaction described by Brown and Clement, providing deep elaboration time and activity, and the conflicting evidence presented, known to help with conceptual change (Russell & Martin, 2007).

Studies of bridging. In a detailed case study, Clement and Steinberg (2002) set out to describe how a sequence of analogies led to revisions of a mental model of electricity for a 16-year-old girl during a summer tutoring session that consisted of five tutoring sessions over two weeks. They found that the student went through four distinct model revisions, each a step closer to a scientifically sound model of a circuit. At each step, a discrepant event was noted to trigger surprise in the subject, a cognitive dissonance that helped initiate revisions in her mental model. She developed a simple, but correct, mental model of an electric circuit.

Clement and Steinberg were able to find patterns for several strategies the student used. One of these was that the tutor introduced an analogy at each point where the student experienced cognitive dissonance. She used these analogies to modify her mental

model. This pattern of dissonance, introduction of analogy from previous knowledge, and adjusting of the mental model was seen over and over again, in a cyclical fashion, a process they termed “GEM” or model generation, evaluation, modification. They used this evidence to argue that mental model building can be an evolution, a process of narrowing through evaluation, rather than a deduction process in which evidence is compiled and then combined to develop a model.

Based on constructivist views of learning, Vygostky’s work with zones of proximal development, and scaffolding, Bryce and MacMillan (2005) studied how 15-year-old students used a series of analogies designed to take them from naïve conceptions to more and more scientifically understanding. Through interviews with 21 students, they tried to detail what each analogy contributed to the understanding of reaction forces. They examined each analogy in terms of whether it contributed to the concept being understandable, plausible and useful in order to foster conceptual change (based on Posner et al., 1982).

The first interview questions were designed to uncover student understandings about forces and reaction forces by having a student explain the forces on a book resting on a table. After the four analogies were demonstrated and experienced, students were asked to rank each for whether it made the existence and cause of the upward force from the table understandable, plausible and useful.

Finally, students were given three novel but analogous scenarios, a person standing on a concrete floor, a book on a table on the moon, and a book on a table in deep space. The latter was considered as more abstract than the others and needing application of knowledge. Students described the understandability, believability, and usefulness of

these scenarios. The researchers coded responses for understandability, defining that as student statements about something making sense. Believability was coded on students' ratings, and usefulness was coded if the student used it in explaining the existence or cause of a reaction force.

Initially, the students taught without a series of analogies traditionally gave mid-range believability ratings and used three or four causes for the forces, giving incorrect or confusing answers, except for one student who tentatively came close. The group that had been previously taught about forces showed even more variability in their explanations but showed predictable misunderstandings about inanimate objects exerting force. The group with no prior instruction about forces relied on their experience with gravity, but rated their beliefs in their answers very low.

The four bridging analogies were rated differently by the students who used them. The first was very understandable and plausible. The second actually led to some misconceptions. The third was the most understandable, believe, and fruitful. At that point, most of the students had scientifically acceptable mental models. The fourth analogy did help some students gain confidence in their explanations. Even at the end, however, some students had dual, competing explanatory mental models.

Usefulness of bridging. Bridging analogies are clearly built on structure mapping theory. They provide evidence for the importance of chunking concepts. Specific analogies need to be chosen to address the development of a scientifically accurate mental model. Students were not explicitly taught metacognitive strategies, though, or made aware of what they were doing. Rather than pointing out where each analogy broke

down, the instructors provided a carefully chosen discrepant event to move the student towards a mental model revision.

In any work with analogies, mental models of the students must be considered. Analogies often provide a more concrete or familiar mental model that can be used to develop a mental model for the unfamiliar or more abstract. However, sequences of bridging analogies may not be available for teaching many science concepts. The bridging model may be useful in some situations. However, it is not practical as a general model of analogy use. It would be time consuming to develop and present the context in which students bridge from one analogy to another for many concepts. Finding and determining the appropriate series of analogies for most science concepts would be difficult for classroom teachers. Finally, there is no evidence that bridging is necessary as a general practice for teaching science concepts.

Need for Current Study

From a cognitivist viewpoint, instructional analogies provide scaffolding for learning. They help learners organize new information or concepts based on schemata already organized and available in long-term memory. To tap into the power of these learning tools, teachers deserve research-based models of effective use. In general, the classroom models of analogy use proposed in the literature have been studied descriptively. Classroom models for analogy use have no theoretical basis and have not been aligned with other educational research findings. We know a great deal about how people learn. We also know how analogies should function within that learning process. We know that students learn differentially in analogy research studies. It stands to reason, therefore, that inconsistent results in studying analogy use may be the result of

inconsistent implementation of the steps students need for using analogies or needs for differentiation among students. There is a need for theoretically based research on how analogies could be used effectively.

The Teaching With Analogies (TWA) model outlines steps for using analogies in classrooms. One of these steps is to specifically map the features of the source to the features of the target. This study examined the importance of including that step in the process of using instructional analogies. There were three research questions guiding the study: (a) Does explicit mapping of the source and target promote more learning than using an analogy without explicit mapping? (b) Do more-knowledgeable and less-knowledgeable learners benefit differentially from mapping? and (c) Are there any benefits that persist over a short time related to either of the first two questions?

CHAPTER 3

METHODS

Design

This study used a 3 X 3 X 3 mixed factorial design. The two between-subjects factors are: 1) Previous Science Knowledge Level (Levels 1, 2, and 3 with Level 1 being the lowest level); and 2) Type of Instruction Module (without analogy, with analogy, or with mapped analogy). The within-subjects factor was test Time (pre-test, immediate post-test, and delayed post-test). The dependent measures were scores of the three tests. Repeated Measures Analysis of Variance (RM-ANOVA) was done to determine statistical significance for main effects for each factor, as well as interactions among the factors.

Factors

Previous science knowledge level. Originally, the study was designed with assignment of each student to a Previous Science Proficiency Level, determined by each subject's eighth-grade science Criterion-Referenced Test (CRT) proficiency level. This statewide, standards-based test is administered towards the end of the eighth grade. However, the school district was not able to provide CRT scores for all of the subjects, so many of the cells were too small for analysis. Instead, scores on the pre-test were used to assign each subject to a Level of Previous Science Knowledge (Level). All subjects scoring 16 or more points on the pre-test were removed, as these scores indicated strong pre-existing knowledge of electrical circuits. The remaining subjects were divided into three groups based on the pre-test scores; this provided a Level 1 group (N = 164) with pre-test scores between 3 and 10 points, a Level 2 group (N = 181) with pre-test scores of

11 or 12 points, and a Level 3 group (N = 211) with pre-test scores between 13 and 15 points. The cut-off points were decided on to group students into similarly sized groups by Level of pre-existing knowledge. The district-provided 8th-grade science CRT scores for a random sample of 83 students were compared to their pre-test scores. There was a correlation of .33, $p < .001$, so the Levels were used in place of the planned proficiency scores.

Type of instruction. Type of Instruction (Module) was a computer-provided lesson about electrical circuits (Appendix B). These lessons were presented as modules within an online learning management system known as Moodle. None of the modules were narrated and none contained animations. All contained multiple graphics related to the text. Module A (no analogy) presented the basic concepts related to electrical circuits. Module B (with an analogy) presented the basic concepts of electrical circuits and included an analogy with water in pipes. The analogy was presented as a graphic of an electrical circuit beside a water pipes circuit and the statement, “A circuit is like a water pipe.” Module C (with a mapped analogy) presented the basic concepts of electrical circuits and each component was explicitly mapped to an analog feature in a circuitous water pipe.

Dependent variables. The dependent variables were the scores on a 20-point, researcher-developed test about electrical circuits (Appendix A). These were a repeated measure, as the same participants took the series of tests. Students were tested before instruction (pre-test), immediately after the instruction (post-test), and after a two-week interval (delayed post-test). Scores on the tests were used to determine if there was change in learning about electrical circuits.

Participants

Data from 556 ninth- and tenth-grade students were used in this study. Characteristics of the sample are shown in Table 2. All subjects were in a year-long, beginning biology course. This required course was designed by the school district based on state standards. The high schools were selected because they had at least 10% of their students who had scored in each of the four levels of science proficiency on the eighth-grade state CRT. Seven teachers at five high schools administered all three components of the study to 21 intact classes. Ninth- and tenth-grade students in biology classes were chosen as the study group for two reasons: (a) the biology course is focused on one science strand, unrelated to the study of electrical circuits, providing ecological validity for effects from the intervention (Shadish, Cook, & Campbell, 2002); and (b) students of this age have been studied by other analogy researchers (Brown & Clement, 1989; Duit et al., 2001; Mason, 2004; Yanowitz, 2001).

Table 2

Characteristics of Participants in Study

	Age[a]		Gender[a]	
	14	15	M	F
N	513	43	207	349
%	92.4	7.6	37.2	62.8

	Ethnicity[a]						
	White	Black	Asian	Hispanic	American Indian	Pacific Islander	Multi-racial or Other
N	302	74	27	118	3	8	24
%	54.4	13.3	4.8	21.3	.5	1.4	4.4

[a]The school district provided birthdates, gender, and the ethnicity coding used by the state.

No previous research was found on which to estimate the probable effect size for the independent variables, making it difficult to estimate sample size based on power or effect size. Factorial designs allow for fewer subjects, but interactions are more difficult to detect with smaller samples (Shadish et al., 2002). A rule of thumb for cell size is to have at least ten more subjects in each cell than dependent variables (Tabachnick & Fidell, 2007). In this study, there were between 44 and 76 subjects per cell.

Procedures

Materials and Instruments

Test construction. A bank of 60 multiple-choice, matching, and true/false questions about electrical circuits was developed. The test questions were prepared based on a set of item specifications for the components of the topic of electrical circuits (Osterland, 2006; Wiggins & McTighe, 2005). The standard related to electrical circuits was first analyzed for component knowledge and skills. Prerequisite knowledge includes: (a) understand that energy has different forms; and (b) list common uses for electricity. It was then determined that the subconcepts that make up understanding electrical circuits include: (a) what electricity is; (b) what the components of an electrical circuit are; and (c) the role of a battery in an electrical circuit. In addition, a vocabulary list was developed (Table 3).

The eighth- and tenth-grade physical science textbooks currently used in this district were examined for questions about electrical circuits. Questions also came from released items from the state criterion-referenced tests, and additional questions were composed by two physical science teachers. Using principles of Understanding by Design (UbD), selected-response questions were written for each of the subconcepts (Wiggins &

McTighe, 2005). Each question was reviewed by three additional high school science teachers and coded as a knowledge/recall question, an understanding of the concept question, or an application of knowledge about the concept question (Osterlind, 2006). Previous studies have shown that students taught with analogies respond differently to different kinds of questions (Yanowitz, 2001). Questions were adjusted until there was a .90 inter-rater reliability. The raters' suggestions for clarity in question stems and distractors were also considered. A balance of recall, understanding, and application questions were chosen for each subconcept, resulting in 60 questions. All questions were then compared against the vocabulary list and wording was adjusted to be consistent with that list

Table 3.

Vocabulary Associated with Electrical Circuits

Battery	Electron	Positive
Bulb	Energy	Switch
Circuit	Field	System
Components	Flow	Transfer
Conduct	Loop	Wire
Current	Mechanism	
Electricity	Negative	

To check that the test questions measured knowledge of electricity, the original bank of questions was field tested with two groups of students, ninth-grade students near the end of their year-long biology class (N = 78, mean age 14.87 years), and a mixture of tenth- and eleventh-grade students near the end of their year-long Automotive Technology course, which included an extensive unit on electricity (N = 81, mean age 15.91 years). Item analysis was done and 15 questions were deleted. On the remaining 45 questions, the biology students scored an average of 56.34% and the automotive students

scored an average of 74.81%. The resulting, smaller bank of questions was a mixture of recall (47%), understanding (36%) and application (18%).

The bank of questions was then organized into three different tests of 20 questions each, Test A, Test B, and Test C. Because each student would take all three tests, they were organized to have equivalent ratios of the different types of questions, different versions of the same question, and different orders for the questions. Only one question of the 45 appeared exactly the same on all three versions of the tests. This meant there was overlap in wording between Test A and Test B of seven questions, between Test A and Test C of eight questions, and between Test B and Test C of six questions. The types of questions for each test are shown in Table 4.

Table 4.

Types of Questions on Each Subtest

	Test Bank	Test A	Test B	Test C
Recall	47%	22%	20%	20%
Understanding	36%	16%	18%	18%
Application	18%	7%	7%	7%

Within the modules, the order of the tests was counterbalanced so that a test order was not associated with a Type of Instruction Module. The bank of questions, as well as Test A, Test B, and Test C, are in Appendix A.

Instruction modules. Three instruction modules about electrical circuits were then developed, with assistance from the teachers who compiled the original bank of test questions. The concepts were listed out, as they were for the test questions, so that the instruction modules mirrored the tests. The modules were then reviewed by two high school physical science teachers and adjusted based on their recommendations. The topic

of electrical circuits was chosen for two reasons: (a) previous research about analogies has been done using the topic of electricity (Chi, 1992; Chiu & Lin, 2005; Clement & Steinberg, 2002; Dagher & Crossman, 1992; Paatz et al., 2004); and (b) electricity is not a topic the subjects receive instruction about during their biology course (Shadish et al., 2002).

Module A, which had no analogy, was composed first. It consisted of text and diagrams. Module A was then adjusted to include a graphic showing an electrical circuit and a circuitous water pipe, labeled "A circuit is like a water pipe." This became Module B. A water pipe was used as the source for the analogy because of its frequent use in previous research about analogies in science education (Chiu & Lin, 2005; Clement & Steinberg, 2002; Paatz et al., 2004; Richland & McDonough, 2010). Module B was then adjusted to include the analogous features of the water pipe beside every diagram of an electrical circuit component. This was Module C. Field testing was done to test whether all of the modules took about the same amount of time for students. The time in the module section was recorded in the Moodle system. Time spent on the modules ranged from four minutes, 17 seconds to 18 minutes, 32 seconds. No statistically significant difference was found in the time students spent on type of modules, $p < .001$. The slides from each Instruction Module are in Appendix B.

Computer use. All three instruction modules were provided using a web-based Moodle learning management system. The Moodle environment is an open-source learning management system, used for online instruction and learning sites (Moodle, n.d.). Instruction components can be built in the system to serve the purposes of the

instruction. It houses a repository of resources used within modules. Users go to a URL provided by the instructor and sign in with a provided login and password.

The Moodle environment for this study contained three modules, A, B, or C. Each module consisted of a pre-test, an instruction module, a post-test, and a delayed post-test. To counterbalance the order of the test forms, there were six different versions of each module, differing only in the order of the test forms. Restrictions were placed so that the participants had to complete the pre-test first. They were not allowed to move on to the instruction module on the same day as the pre-test. The instruction portion of the module had to be viewed before the post-test was activated. The participants were not allowed to move on to the delayed post-test until two weeks had passed after the instructional module and post-test.

Each student used his or her district-generated student number as both the login and password. Each student number was assigned to a specific version of one of the three modules and could not be used to login to any other modules. For example, if a student was randomly assigned to Pre-test B, Module A , Post-test C, and Delayed Post-test A, that student could only access those components and in that order. All students used either their school's existing computer lab or a laptop cart in the science classroom to log into the Moodle and access the materials, under the supervision of their classroom teacher.

Assignment to Conditions

Each subject was randomly assigned to one of the three modules, with counterbalanced test forms, in the Moodle learning management system. This random assignment was done with a random number generator, using each teacher's group of

students as a sample, not each class of students. Level of science knowledge was not considered in assignment to conditions, as students were grouped by level only for analysis.

Timeline

This study took place over a six-week period, from September 27 – November 2, 2012. Teachers continued regularly scheduled classroom instruction between the administration of the post-tests and the delayed post-tests. Data analysis was done during November and December, 2012.

Student Activities

Students first took a 20-question, multiple-choice pre-test about electrical circuits. Three of the teachers chose to use paper and pencil versions of the tests and gave them to the researcher for scoring. The other four teachers had their students do the pre-test in the Moodle system. The teachers requesting paper and pencil versions did so because of scheduling. High school computer labs and equipment are heavily scheduled and some were not able to schedule labs for a 10-minute test. No statistically significant differences in means were found among the test forms for those taking them paper and pencil or online, $p < .001$.

Within a week of the pre-test, all students completed their assigned modules and post-tests in a computer lab or with laptops in mobile carts. All of the instruction modules and the post-tests were done online. After a slight delay of two weeks, students then took either a paper and pencil or online multiple-choice post-test about electrical circuits, again based on their teachers' abilities to schedule computer equipment. All forms of all tests were either scored by the Moodle system or electronically through the use of

researcher-provided answer sheets that could be scanned. Because the sample size was large enough, no teachers were asked to have absent students make up any missed components. In each class, there was a small percentage of students without parent permission, student permission, or both. I provided paper and pencil or electronic crossword puzzles about cells for those students, so that the students were not singled in any way and the teachers did not have to plan for alternative instruction. None of these activities were collected, scored, or analyzed.

Analysis

Data Preparation

For each student, the raw score on the pre-test, post-test, and delayed post-test was entered into a data set. For the Level factor, students were assigned to a group based on pre-test scores, and a code of 1 (pre-test scores of 3 - 10), 2 (pre-test scores of 11 or 12), or 3 (pre-test scores of 13 – 15) proficient) was entered for each student. For the Type of Instruction Module factor, a code of 1 (Module A with no analogy), 2 (Module B with analogy), or 3 (Module C with mapped analogy) was entered for each student. Descriptive information (gender, age, ethnicity, and teacher) for each student was also entered.

Data were collected from 714 students. Data were screened to see that every subject had been assigned to a module and had data from the pre-test. As the first step in data screening, results from 11th- and 12th-graders and those over the age of 15 years old were removed, as they were outside of the intended sample population. For the second step, results were removed for students who scored 16 points or higher on the pre-test, as

that indicated they understood electrical circuits well before instruction. This was done to address a probable ceiling effect. At that point, 580 cases remained.

IBM SPSS®, version 21, was then used to screen for multivariate outliers, using the “unusual cases” command and pre-test, post-test, and delayed post-test as variables. This identified 24 unusual cases, ranging in impact from .38 to .85. At that point, Mahalanobis Distance maximum was16.10, below the critical χ^2 value of 20.52 for five variables.

Table 5.

Number and Level of Knowledge of Subjects per Cell

Level of Knowledge	Type of Instruction			
	Module A	Module B	Module C	Total
Level 1	N = 59	N = 44	N = 61	N = 164
Level 2	N = 54	N = 66	N = 61	N = 181
Level 3	N = 66	N = 76	N = 69	N = 211
Total	N = 179	N = 186	N = 191	N = 556

As the final step of data preparation, I considered deleting the data for the subjects who did not complete the delayed post-test. However, test statistics from an ANOVA indicated that there were statistically significant differences between those who completed the delayed post-test and those who did not, specifically on their pre-test scores, $F(1,554) = 4.06$, $p = .044$, and on their post-test scores, $F(1,554) = 11.09$, $p = .001$. Therefore, data from those without delayed post-test scores were included in the analysis and listwise allowances for missing data were used in analysis.

Sample size. The final number of subjects was 556. After listwise deletions during analysis, the analyzed sample size was 503. Tabachnick and Fidell (2007) suggest that each cell should have 10 more subjects than there are dependent variables. In this study, the smallest group of subjects was 44 and the largest was 69. See Table 5 for sample sizes.

Data Analysis

SPSS®, version 21, was used to conduct a Repeated Measures Analysis of Variance (RM-ANOVA) on the dataset. This is an approach in which the dependent variables, in this case scores on the pre-test, post-test, and delayed post-test, are highly correlated and are measures from the same participants.

The between-subjects factors were Type of Instruction Module (with three types as described above, Module A, Module B, and Module C) and Level (Level 1 for pre-test scores less than or equal to 10, Level 2 for pre-test scores of 11 or 12, and Level 3 for pre-test scores between 13 and 15). The within-subjects factor was Time (pre-test, post-test, and delayed post-test). The dependent variables were the Scores on the pre-test, post-test, and delayed post-test.

First, analysis was done to measure any interactions among Module, Level and Time, based on the first research question for this study. Follow-up univariate tests were then done to measure any interactions between pairs of independent variables. Next, the main effects for statistically significant interactions were tested. Finally, tests on simple effects and pairwise comparisons were done in order to determine which of the variables had an effect on learning, as measured by the scores on the post-test and delayed post-test.

Assumptions

Normality. Kurtosis and skewness were tested for the dependent variables, pre-test, post-test and delayed post-test. For the pre-test, skewness was -.559 and kurtosis was .319. For the post-test, skewness was -.433 and kurtosis was -.036. For the delayed post-test, skewness was -.290 and kurtosis was -.121. All of these indicate reasonably normal distribution in the repeated measures.

Linearity. Scatterplots were used to visually examine linearity among variables. No transformations were necessary.

Homogeneity of variance. The homogeneity of variance (Box's M) was rejected, $p < .001$. This is not unusual with large sample sizes in each cell. However, Pillai's trace was used to evaluate multivariate significance.

Sphericity. Sphericity indicates whether there is a pattern in the variance/covariance matrix of the observed data. This assumption did not hold, not unexpected with repeated measures, Mauchley's W = .906, $\chi 2$ (2) = 42.10, $p < .001$; therefore Huynh-Feldt epsilon was used for adjustments when testing significance.

CHAPTER 4

RESULTS FROM THIS STUDY

Interactions

The first test was for an interaction among all independent variables: Instruction, Level, and Time. The means and standard deviations are below (Table 6) for each of the factorial groups.

Table 6.

Means and Standard Deviations for Each Factorial Group

		Time		
Group	*N*	Pre-test *M (SD)*	Post-test *M (SD)*	Delayed Post-test *M (SD)*
Module A	**163**	**11.63 (2.14)**	**14.34 (2.84)**	**13.49 (3.00)**
Level 1	55	9.22 (1.07)	12.96 (2.88)	11.53 (2.62)
Level 2	47	11.53 (0.50)	14.30 (2.64)	13.70 (2.82)
Level 3	61	13.89 (0.79)	15.61 (2.37)	15.10 (2.42)
Module B	**164**	**11.80 (2.05)**	**14.39 (2.58)**	**13.40 (2.86)**
Level 1	35	8.83 (1.40)	13.00 (2.85)	12.23 (2.57)
Level 2	62	11.40 (0.50)	14.44 (2.09)	13.19 (2.35)
Level 3	67	13.72 (0.78)	15.07 (2.58)	14.21 (3.20)
Module C	**176**	**11.44 (2.29)**	**14.20 (2.75)**	**13.36 (2.92)**
Level 1	58	8.81 (1.52)	13.12 (2.78)	12.05 (3.26)
Level 2	56	11.61 (0.49)	14.45 (2.54)	13.64 (2.69)
Level 3	62	13.76 (0.78)	14.98 (2.62)	14.32 (2.31)
Total	**503**	**11.62 (2.17)**	**14.31 (2.72)**	**13.42 (2.92)**

Multivariate tests found no statistically significant interaction among Time (pre-test, post-test, and delayed post-test), Level of previous knowledge of electrical circuits (Level 1, Level 2, Level 3), and Module (Module A, Module B, Module C), $F(8,988)$ =

1.11, p = .351, partial η^2 = .009. Scores did not vary differently as a function of different combinations of modules and levels.

Time and Module

Nor was there a statistically significant interaction between Time and Module, $F(4,988) = 0.07$, p = .992, partial η^2 = .000. The test scores for each time of testing did not change differently based on the type of instruction. In other words, the pre-test scores were statistically similar for all three Modules, as were the post-test scores and the delayed post-test scores. Those subjects randomly assigned to Module A had scored an average of 11.63 questions correct on the pre-test, those randomly assigned to Module B had scored an average of 11.80 questions correct on the pre-test, and those randomly assigned to Module C had scored an average of 11.44 questions correct on the pre-test. None of these were statistically distinguishable from the pre-test average score of 11.62 points correct. This pattern was similar for the post-test results and the delayed post-test results. The post-test average scores were 14.34, 14.39, and 14.20 respectively for Modules A, B, and C, statistically indistinguishable from the post-test average score of 14.31. The delayed post-test average scores were 13.49, 13.40, and 13.36 respectively for Modules A, B, and C, statistically indistinguishable from the delayed post-test average score of 13.42. See Figure 1.

Level and Module

No statistically significant interaction between Module and Level was found, either, $F(12,1482) = .99$, p = .454, partial η^2 = .008. Specifically for the pre-test, no statistically significant interaction between Module and Level, $F(4,494) = .99$, p = .412 was found. This indicates that no Module-related differences in pre-test scores exist,

within each Level. The random assignment to Modules assured that each Level's pre-test scores were statistically similar. Level 1 subjects randomly assigned to Module A had scored an average of 9.22 questions correct on the pre-test, those randomly assigned to Module B had scored an average of 8.83 questions correct on the pre-test, and those randomly assigned to Module C had scored an average of 8.81 questions correct on the pre-test. The differences between Modules were very similar for Level 2 subjects for the pre-test, with averages of 11.53, 11.40, and 11.61 questions correct for those assigned to Modules A, B, and C respectively. The differences between Modules were also very similar for Level 3 subjects for the pre-test, with averages of 13.89, 13.72, and 13.76 questions correct for those assigned to Modules A, B, and C respectively. On the pre-test, none of the Levels, on any Module, scored notably different than their Level's average score for that Module.

Of interest for the second research question, the data were examined for differences in post-test scores because of interactions between Level and Module. None were found. The differences were not statistically significant, $F(4,494) = .50$, $p = .737$, partial $\eta^2 = .004$, and indicated no practical significance. For Level 1 subjects, the post-test averages were 12.96, 13.00, and 13.12 respectively for Modules A, B, and C, and similar to the Level 1 average on the post-test of 13.03. For Level 2 subjects, the post-test averages were 14.30, 14.44, and 14.45 respectively for Modules A, B, and C, and similar to the Level 2 average on the post-test of 14.40 points. For Level 3 subjects, the post-test averages were 15.61, 15.07, and 14.98 respectively for Modules A, B, and C, and statistically similar to the Level 3 average on the post-test of 15.22 points.

The data were then examined for differences in delayed post-test scores because of interactions between Level and Module. Again, none were found. The differences were not statistically significant, $F(4,494) = 1.43$, $p = .224$, partial $\eta^2 = .011$, and indicated no practical significance. For Level 1 subjects, the delayed post-test averages were 11.53, 12.23, and 12.05 respectively for those assigned to Modules A, B, and C, and were statistically indistinguishable from the Level 1 average on the delayed post-test of 11.90 points. For Level 2 subjects, the delayed post-test averages were 13.70, 13.19, and 13.64 respectively for those assigned to Modules A, B, and C, and were statistically similar to the Level 2 average on the delayed post-test of 13.49 points. For Level 3 subjects, the delayed post-test averages were 15.10, 14.21, and 14.32 respectively for those assigned to Modules A, B, and C, and were statistically similar to the Level 3 average on the delayed post-test of 14.53 points.

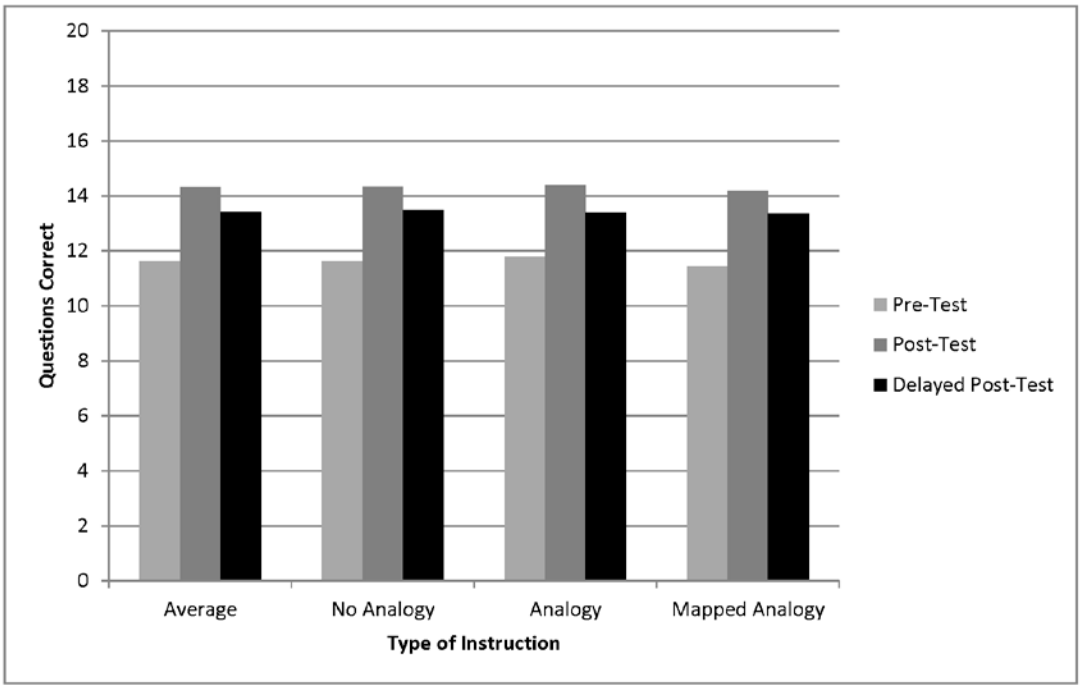


Figure 1. Test Scores for Each Type of Module.

Modules

The type of instruction, with no analogy (Module A), with an analogy (Module B), or with an explicitly mapped analogy (Module C), had no different effects on test scores. All three types of instruction led to the same amount and pattern of learning, as described later.

Time and Level

A statistically significant interaction between Time and Level was found, $F(4,988) = 20.93$, $p < .001$, partial $\eta^2 = .078$. The scores from each Level of subjects changed differentially over time. At all three test times, the scores from each Level were statistically different from both the previous test time and from the other Levels. For the pre-test, the scores among Levels were significantly different, $F(2,500) = 1145.29$, $p < .001$, partial $\eta^2 = .82$, as were the scores between Levels on the post-test, $F(2,500) = 30.06$, $p < .001$, partial $\eta^2 = .11$ and the scores between levels on the delayed post-test, $F(2,500) = 39.02$, $p < .001$, partial $\eta^2 = .14$.

Of more interest to this study, the effect of instruction, based on the differences between pre-test scores, post-test scores, and delayed post-test scores were different for each Level of previous knowledge of electrical circuits. Post hoc tests, using multiple comparisons and reporting Bonferroni corrections, showed the mean difference in scores between Levels narrowed between the pre-test and post-test, and expanded between the post-test and delayed post-test, although not to the original mean differences. The mean difference on the pre-test between Level 1 subjects and Level 2 subjects was 2.56 points, $p < .001$, and this narrowed to a mean difference of 1.37 points, $p < .001$, after instruction and a mean difference of 1.58 points, $p < .001$, two weeks after instruction. The gap

between the Level 1 subjects and the Level 2 subjects narrowed after instruction and stayed narrowed after a slight delay. The mean difference on the pre-test between Level 2 subjects and Level 3 subjects was 2.27 points, $p < .001$, and this narrowed to a mean difference of 0.83 points, $p < .003$, after instruction and a mean difference of 1.03 points, $p < .001$, two weeks after instruction. After instruction, the gap between Levels 2 and 3 subjects narrowed and stayed narrowed. The most dramatic narrowing was between Level 1 and Level 3 subjects. The mean difference on the pre-test between Level 1 subjects and Level 3 subjects was 4.83 points, $p < .001$, and narrowed to 2.19 points, $p < .001$, after instruction and a mean difference of 2.61 points, $p < .001$, two weeks after instruction.

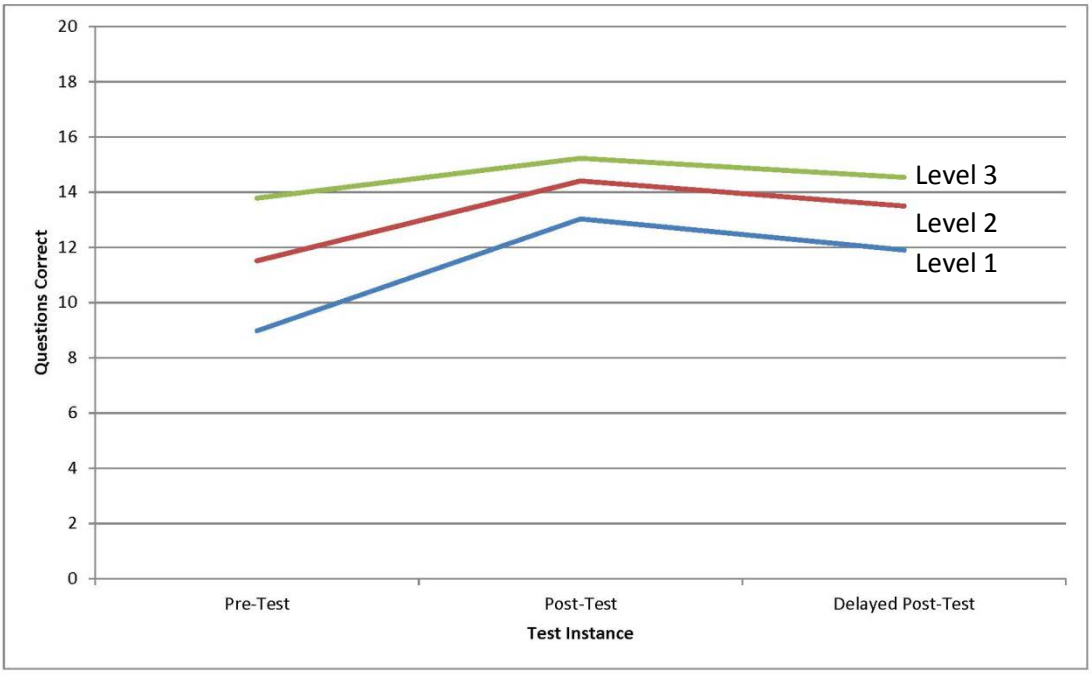


Figure 2. Change Over Time by Different Levels.

All three Levels of subjects made gains after instruction and then their scores decreased on the delayed post-test, although not to pre-instruction scores. The Level 1 subjects made the most gains and the gaps between them and their counterparts narrowed.

Their mean on the post-test was 13.03 points, 5.06 points higher than their starting mean of 8.97 points. Their mean on the delayed post-test was 11.90 points, 1.13 points lower than their post-test mean, but still 2.93 points higher than their pre-test mean. Level 2 subjects had a mean score of 14.40 points on the post-test, 2.89 points higher than their pre-test mean of 11.51 points. Their mean on the delayed post-test was 13.49 points, 0.91 points lower than their post-test mean but still 1.98 points higher than their pre-test mean. Level 3 subjects benefitted from instruction the least. Their mean on the post-test was 15.22 points, 1.44 points higher than their pre-test mean of 13.78. Their mean on the delayed post-test was 14.53, 0.69 points lower than their post-test mean but still 0.75 points higher than their pre-test mean.

Time

Within subjects, the differences between the pre-test, post-test, and delayed post-test scores were statistically significant, $F(2,988) = 287.09$, $p < .001$, partial $\eta^2 = .37$, with Huynh-Feldt epsilon corrections for sphericity. Practically, time had a medium effect on the scores. Post hoc pairwise comparisons, using Bonferroni adjustments for multiple comparisons, indicated that there was a significant mean difference increase between pre-test scores and post-test scores of 2.80 points, $p < .001$, a significant mean difference decrease between post-test scores and delayed post-test scores of 0.88 points, $p < .001$, and a significant mean difference increase between pre-test scores and delayed post-test scores of 1.91 points, $p < .001$. For all Levels, subjects scored higher after instruction. Then, after a slight delay of two weeks, their scores dropped slightly (Figure 2).

Level

Statistically significant differences were found between all Levels for every test administration. It follows that, between subjects, the differences on combined scores were statistically significant, $F(6,998) = 116.32$, $p < .001$, partial $\eta^2 = .41$. Practically, Level had a medium effect on the scores. Level 1 subjects scored the lowest combined scores, and Level 3 subjects scored the highest. Post hoc pairwise comparisons, using Bonferroni adjustments for multiple comparisons, indicated a significant mean difference of 1.97 points, $p < .001$, between Level 1 subjects' scores and Level 2 subjects' scores, a significant mean difference of 1.47 points, $p < .001$, between Level 2 subjects' scores and Level 3 subjects' scores, and a significant mean difference of 3.44 points, $p < .001$, between Level 1 subjects' scores and Level 3 subjects' scores. Each group designated as a Level was a statistically distinct subset (Tukey HSD), $p < .05$.

In summary, all groups benefitted from the instruction, both immediately after instruction and after a slight delay of two weeks; however, the type of instruction made no statistical difference.

CHAPTER 5

DISCUSSION AND IMPLICATIONS

This section discusses the results of this study within the context of the Teaching With Analogies (TWA) model. A summary of the study's findings is presented first, followed by implications for instruction, limitations of this study, and suggestions for further research.

Summary

Three research questions shaped this study: 1) Does explicit mapping of the source and target when using an analogy promote more learning than using an analogy without explicit mapping? 2) Do more-knowledgeable and less-knowledgeable learners benefit differentially from mapping? 3) Are there benefits over a short time related to either of the first two questions?

The results from this study found no benefit for explicitly mapping source and target over simply presenting an analogy. I also found no benefit for using analogy over presenting the information without an analogy. Subjects scored significantly higher on the post-test after receiving instruction; however, no differences existed in the gains based on the type of instruction they received. Although the group that received instruction with an explicitly mapped analogy made the largest gain between the pre- and post-tests, it was not statistically different than the gains made in all instruction groups. These results suggest that students learned about electrical circuits from all three types of instruction.

For the second research question, I found that the type of instruction provided did not differentially benefit a specific group of student, based on their previous knowledge

of the topic. Whether students knew very little about electricity, or were closer to a mastery level, they benefitted equally from all three types of instruction. The average gain between the pre-test and post-test was about the same, statistically, for those who got no more than half of the pre-test questions correct, those who got 11 or 12 pre-test questions correct, and those who got 13 to 15 of the pre-test questions correct. These results suggest that the type of instruction did not impact learning differentially for those with different levels of previous knowledge.

The third research question was worthwhile only if benefits were found in the first two questions. For all three types of instruction and across all three levels of students, the same pattern emerged over time. Students made statistically significant gains between the pre-test and post-test, after instruction. The scores then dropped slightly on the delayed post-test but were still significantly different than the scores from the pre-test and from the post-test. These results suggest that students learned from the instruction and, two weeks later, evidence was found of learning, although not as much as right after instruction. Going back to the first two research questions, no statistically different patterns emerged based on either type of instruction, previous knowledge, or an interaction among them.

Implications for Instruction

The Teaching With Analogies (TWA) model of instruction was developed through examination of high school science textbooks and consists of six steps to use in classrooms: (a) introducing the target concept; (b) recalling a source concept; (c) identifying similar features; (d) mapping similar features; (e) drawing conclusions about the concepts; and (f) noting where the analogy breaks down (Glynn, 1991; Glynn et al.,

1989). This study, in an attempt to start gathering quantitative evidence for this model, focused only on the third and fourth steps. Evidence was found that identifying similar features and mapping them between the source (in this case, a circuitous water pipe) and the target (in this case, an electrical circuit) helped students learn. However, statistically, the learning was not any stronger or weaker than the learning from the instruction that only used step one (no analogy) or the instruction that used steps one and two (with an unmapped analogy).

Previous research has produced mixed results on whether instruction with analogies fosters learning in science education (Dagher et al., 1993; Glynn et al., 1989; Oliva et al., 2007; Pramling, 2009; Yanowitz, 2001), so the results of the analogy instruction in this study are not surprising. Glynn and Takahashi (1998) found the same pattern of increased recall and recognition of concepts immediately after instruction with analogies and a small decrease in the same after two weeks.

Science teachers naturally use analogies (Dagher, 1995b; Dagher & Crossman, 1992; Duit et al., 2001; Glynn, 2008), as do parents (Valle & Callanan, 2006), and working scientists (Coll, 2006; Dunbar, 2001; Holyoak, 2005). Analogies are a frequently used tool and will continue to be used. The question before educators is about the best way to scaffold and differentiate for each student by presenting and using analogies for learning. The importance of differentiating instruction to find the most effective way to reach each student is not lost on teachers (Allen & Tomlinson, 2000). Based on this study, the time and resources for explicitly mapping the features of the analogy may not be needed. If educators are going to use the TWA model of instruction, they may need to

critically evaluate the benefits to ensure that limited resources, such as instructional time, are used effectively.

Other benefits may come, though, from using explicitly mapping analogies, such as peaking interest or refuting misconceptions. For example in studies done by Glynn and Takahashi (1998) and Paris and Glynn (2004), evidence was found that the participants found explanations that used the components of the TWA model significantly more interesting. These types of benefits were not tested in this study. However, a random sample of 79 students from the study found no statistically significant differences in the time students spent on the three instruction modules, $p < .001$. If students found one module more interesting than another, as a group they did not spend measurably more time in it. Many components influence learning, and it is prudent to consider as many as possible in making instructional decisions.

It may also be that the Modules were helpful to students on different kinds of questions. It was outside the scope of the study; however, some of the previous research has shown that analogies can help some students answer better on questions that require higher order skills, such as making inferences (Yanowitz, 2001).

For any model of instruction that may be used in science classrooms, all of the components of the model should be tested for efficacy, along with the interactions among the components, in a variety of environments, to ensure that classroom instruction practices can be based on evidence. In this study, no quantitative evidence was found for the need to explicitly map the features of the source and target in an analogy for an electrical circuit in a computer-based instruction module. At the same time, the explicitly mapped analogy led to the same scores on the post- and delayed post-tests as instruction

with an unmapped analogy and with no analogy. It was useful to the students, but not measurably more useful than the other types of instruction.

Limitations of This Study

Limitations exist in all educational research. Acknowledged limitations of this study may have influenced the results. First of all, this study was done within a limited age group. All students were 14- or 15-years-old and in either 9th- or 10th-grade. Younger students may benefit differently from the different types of instruction. Along with this, it is always best to be cautious about generalizing from a specific sample. These students were from five large, urban high schools within one school district. Their teachers did not volunteer, but they did have a choice about allowing their classes to participate. It may be that results would be more conclusive with a different sample.

Second, a single topic or concept was used. While this was done to eliminate variability in instruction, it may be that the topic of electrical circuits was not appropriate for identifying any effects. Another possibility exists that these students had already studied electrical circuits and did not need scaffolding from the analogy. Perhaps the instruction modules served as reminders of previous knowledge, rather than new understanding. This would be one way to account for the pattern of low pre-test scores, then significant increase in post-test scores after the instruction modules. The statistically significant drop in test scores on the delayed post-test, however, would not necessarily support this explanation. Along with a single topic, a single analogy was used. There may be other analogies that would be more useful to the students when learning about electricity.

Third, the Instruction Modules may not have been different enough to allow identification of interactions or effects. This study was also done with a single instance of computer-based instruction. It may be that explicitly mapping an analogy is important in a more extensive unit of instruction or when used in teacher-to-student or student-to-student interactions. Blakes' study (2004) using 9- through 11-year-olds, for example, was done over an extensive unit of instruction.

Finally, the instrument used to measure learning may not have been appropriate for identifying interactions or effects. It was a researcher-developed tool, and was developed to measure conceptual knowledge as a mixture of recall, understanding, and application questions. It did not purport to measure other valuable components, such as making inferences, sparking interest, or refuting misconceptions.

Next Steps

Replication of Study

I would suggest a replication of this study about explicitly mapping features of analogies, with some differences that may shed light on analogy use. First, the study could be replicated with different science concepts. It would be especially important to find a topic about which students had never been taught, as well as an analogy the students had not used. This could shed light on whether students in this study used all three modules to activate prior knowledge or to learn.

I would also suggest that the instruction modules be more extensive, perhaps as units, rather than single, short lessons. This would provide information about whether analogies are measurably useful during lessons similar to those used in classroom

settings. I suggest that explicit mapping of analogies be examined in both teacher-led classroom settings and with computer-based instruction.

Other Benefits of Explicitly Mapping Analogies

Secondly, data should also be gathered on whether or not students find explicitly mapped analogies more interesting or more understandable than either instruction without analogies or instruction with unmapped analogies. Benefits from explicitly mapped features may not be tied directly to learning. These research questions would benefit from qualitative studies, also, to provide a more descriptive picture of how students learn from explicitly mapped features in analogies. Across a variety of topics and student ages, this could inform educators about the use of analogies to help learning through important aspects such as motivation and perseverance. Student misconceptions are a frequent concern in science education (Aubusson, 2006; Blake, 2004; Brown & Clement, 1989; Coll, 2006; Heywood, 2002; Vosniadou, 2007); further research with analogies could be shaped to study whether analogies are useful in helping students develop canonical understandings. Dunbar (2001) points out that analogy use under the examination of research is very different from the natural use of analogies. He suggests that research settings remove much of the opportunity for elaboration and change the goals of those being studied.

Third, data should be gathered on whether the step of explicitly mapping analogies impacts the type of questions students are able to answer best. Yanowitz (2001) found that analogies were not especially useful for recall questions; however, Glynn and Takahashi (1998) found they were. In this study, care was taken to include a variety of types of questions on the test to measure learning, but analysis of the relationships

between the types of instruction and the types of questions was outside of the scope of the study.

Explicit Mapping as Part of a Complete Model

Finally, explicit mapping may be studied in combinations with the other components of the TWA model. This study looked at only identifying and explicitly mapping an analogy. Further research could provide data on the effects of interactions within the components of the model. It may be that learning is impacted differently by using all of the components of the TWA model. All analogies break down. It would be important to test this, in a variety of settings, with different topics, and across different ages of students.

APPENDIX A

TEST BANK

1. The path through which a current flows is called a
    a. bulb.
    b. circuit.
    c. volt meter.
    d. battery.

2. A circuit is a path through which a _____ flows.
    a. current
    b. circuit
    c. volt meter
    d. battery

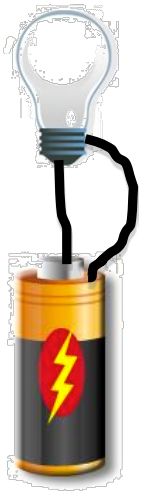
3. Material that is a conductor has _____ that can move from atom to atom.
    a. Free electrons
    b. Current
    c. Wires
    d. Positive particles

4. Which of these bulbs will light?

a.

a.

b.



c.

d. All of them

e. None of them

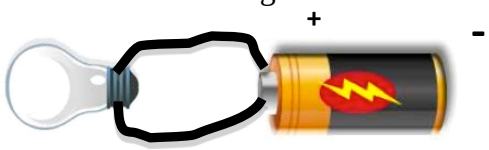
5. What does a battery do in an electrical circuit?
    a. Pushes and pulls the current through the circuit.
    b. Sends electricity to a bulb.
    c. Sends an electron from one end of the wire to another.
    d. Uses energy to push the light to the bulb.

6. Why does a bulb in a circuit light instantly?
    a. The electrons move to the bulb very quickly, faster than we can see.
    b. There are electrons all along the conductor (wire) and they repel the negative charge from electron to electron.
    c. The battery has a lot of energy and pushes it very quickly to the bulb where it turns into light energy.
    d. The wire is a superconductor that carries the electricity to the bulb faster than we can measure.

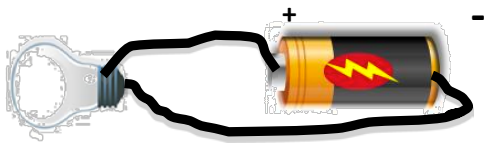
7. Your friend asks you why he doesn't feel a shock when he puts his hand near a battery. The best explanation is that
    a. A battery has to be connected to a switch that you turn on.
    b. A battery only works if there is something that needs to be turned on.
    c. The air between the battery and his hand is an insulator, not a conductor.
    d. The electrons go out into the air without a path to follow, so they don't get to his hand.

8. Is there a current in this piece of wire?
    a. Yes, because it is a complete circuit.
    b. Yes, because it is filled with electrons that repel each other.
    c. No, because it is not a conductor, so the circuit cannot be complete.
    d. No, because there is nothing to start the electrons moving.

9. This circuit would not work because
    a. Electricity has to flow to the bulb out of both ends of the battery.
    b. The current leaves the negative pole and needs to return through the positive pole.
    c. The wires are attached to the wrong end of the battery.
    d. The current would go through the light bulb because it follows the wire.



10. This circuit would work because



a. Electricity has to flow to the bulb out of both ends of the battery.
b. The wire can conduct the current through both sides of the bulb.
c. The current gets used up in the light bulb and drains the battery.
d. The current leaves the negative pole and returns to the positive pole.

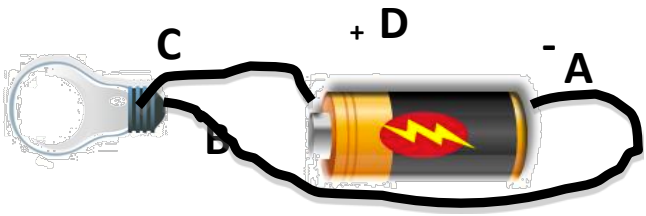
11. What happens when a negative charge is pushed towards an electron by a battery?
a. A negative charge repels a negative charge, moving the charge from electron to electron.
b. A positive charge repels a positive charge, moving the charge from electron to electron.
c. A negative charge is attracted to the electron, moving the charge from electron to electron.
d. A positive charge is attracted to the electron, moving the charge from proton to proton.

12. How is the current returned to the battery?
a. The current does not return to the battery and is used up in the bulb.
b. The current is pushed from one end of the battery and pulled from the other.
c. The current moves through the conductor until it comes to a gap.
d. The current moves through the insulator and back to the battery.

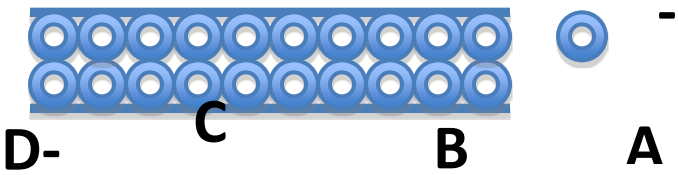
13. Why does a battery need a positive end?
a. The negative end attracts electrons and the positive end repels them.
b. The positive end attracts electrons, pulling the charge through the circuit.
c. The positive end sends out a negative charge, pushing it through the circuit.
d. The positive end grounds the circuit so that the electricity cannot escape.

14. What makes the light bulb glow?
a. The electricity is being changed and released as light energy.
b. The electrons react with the thin wire inside the light bulb, producing light.
c. The current meets resistance when it reaches the thin wire in the bulb and light energy is produced as the current moves past.
d. The battery sends energy to the bulb through the wires to light up the bulb.

15. Which sequence shows the correct flow of the current?
    a. A to B to C to D
    b. A to D and A to B
    c. A to B and D to C
    d. D to C and C to D



16. This diagram represents electrons in a conducting wire. How does the charge get from A to D?



    a. The electron entering at A gets repelled through the electrons to D.
    b. The negative charge entering at A repels the negative charges from the electrons near B to towards the electrons near C. The negative charge near C gets repelled towards D.
    c. The electron from A moves between the electrons near B, to C, and then leaves at D.
    d. The negative charge entering at A is attracted to the electrons near B and then towards the electrons near C. The negative charge near C is attracted towards D.

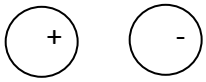
Match these terms and definitions.

17. Electron	a. a substance with free electrons
18. Proton	b. a positively charged particle
19. Battery	c. a source of energy that pushes charges
20. Conductor	d. a flow of charges
21. Current	e. a negatively charged particle

True or False?

22. Electricity can flow through a broken wire as long as the break is not really large.
    a. True b. False
23. The current coming back into the battery is used up when it gets there.
    a. True b. False
24. Copper wires are wrapped in plastic because plastic is not a conductor.
    a. True b. False
25. A current leaves the positive end of a battery and returns through the negative end.
    a. True b. False
26. Electrons move very, very slowly through a conductor.
    a. True b. False
27. A switch can be used to open and close a circuit.
    a. True b. False
28. There is resistance when the current reaches the thin wire in a bulb and the thin wire heats up.
    a. True b. False
29. Negative charges repel negative charges.
    a. True b. False
30. Charges move very, very slowly through a conductor.
    a. True b. False
31. A circuit is the path that charges follow.
    a. True b. False
32. The charges in the circuit that come back into a battery can re-charge it.
    a. True b. False

33. Which of the following are necessary for an electrical circuit?
    a. Conductor, bulb, switch
    b. Battery, conductor
    c. Bulb, conductor, battery
    d. Battery, bulb

34. Electricity is the movement of electric charge from one place to another.
    a. True b. False
35. Like charges repel and unlike charges attract.
    a. True b. False
36. What will happen with these particles? 

    a. They will move away from each other.
    b. They will stay where they are.
    c. They will move towards each other.
    d. They will move back and forth.

37. Glass is an insulator because it has no
    a. Electrons and protons.
    b. Wires inside it.
    c. Free electrons.
    d. Electrical source.

38. Why are metals good conductors?
    a. They have lots of negatively charged electrons.
    b. They carry electrons very fast.
    c. They are not made of glass.
    d. They have free electrons that can move.

39. Why don't we sense electrical forces between us and our environment?
    a. Electrical forces need a path to follow.
    b. Electrical forces are very, very weak.
    c. Electrical forces are very, very strong.
    d. Electrical forces need a battery or plug.

40. Why don't the electrons in a penny jump out?
    a. There are no free electrons in a penny.
    b. They don't have a battery to charge them.
    c. Electrons need a path to follow.
    d. The penny has protons that repel the electrons.

41. What is the source for the electrons that move in a current?
    a. The battery supplies electrons.
    b. The conductor is full of electrons.
    c. The insulator is full of electrons.
    d. The bulb sends out the electrons.

42. Do more electrons flow out of a battery than into it?
    a. Yes, that is why the battery doesn't last forever.
    b. No, the battery pushes electrons from one end and pulls them from the other.
    c. Yes, the battery sends electrons to the light bulb where they turn into light energy.
    d. No, the battery creates electrons that flow out into the conductor and through the circuit.

43. Are the electrons flowing in the circuit provided by the battery?
    a. Yes, that is why the battery doesn't last forever.
    b. Yes, the battery sends electrons to the light bulb where they turn into light energy.
    c. No, the battery creates electrons that flow out into the conductor and through the circuit.
    d. No, the battery pushes electrons in the conductor from one end and pulls them from the other.

44. What happens if there is a gap in the circuit?
    a. The current must cross the gap and that takes more energy.
    b. The current does not have a path and stops.
    c. The current must create a path and keep going.
    d. The current goes out into the gap and creates a shock.

45. What are the two kinds of electrical charge?
    a. Positive and neutral.
    b. Negative and balanced.
    c. Positive and balanced.
    d. Negative and positive.

Components of Test A, Test B, and Test C

R = Recall

K = Knowledge/Understanding

A = Application

Question	Test Bank	Test A	Test B	Test C
1	R	R	R	
2	R			R
3	R	R		R
4	A		A	
5	K	K		
6	K	K		K
7	A	A		A
8	A		A	
9	A	A		
10	A			A
11	K		K	K
12	K	K		K
13	A	A	A	
14	R		R	
15	K	K	K	
16	K		K	
17	R	R		
18	R		R	
19	R	R	R	R
20	R	R	R	R
21	R	R	R	R
22	K	K		
23	R		R	
24	K		K	K
25	R		R	
26	R	R		
27	R			R
28	R			R
29	R	R		
30	R		R	
31	R			

Question	Test Bank	Test A	Test B	Test C
32	K			K
33	K	K		
34	R	R		R
35	R			
36	K			K
37	R	R		
38	K		K	
39	A			
40	A			A
41	K	K	K	
42	K			K
43	K		K	K
44	K		K	
45	R			R

APPENDIX B

INSTRUCTIONAL MODULES

Electricity

Module A

Review of Atoms

- All matter is made of atoms.
- Atoms consist of three types of particles.
  - Protons are positively charged (+).
  - Neutrons are not charged.
  - Protons and neutrons are in the nucleus of the atom.
  - Electrons are negatively charged (-) and move around the nucleus.

Charged Particles

- Remember that negative charges repel or push away from each other.
- Positive charges are attracted to or move towards negative charges.

Conductors

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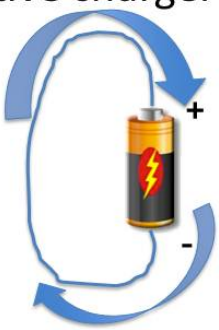
- A material made of atoms with free electrons is a conductor. Copper atoms, for example, have free electrons. Copper conducts electrical current.

Insulators

- Atoms that do not have free electrons make up matter that insulates or does NOT conduct electricity.
- The electrons in plastic, for example, do not move easily from one atom to another. Plastic is an insulator; it does NOT conduct electrical current.

Electrical Circuits

We often think of an electrical circuit as starting with a battery. In a battery, a chemical reaction causes a negative charge to move away from a terminal, if there is a path. The other terminal attracts the negative charge.

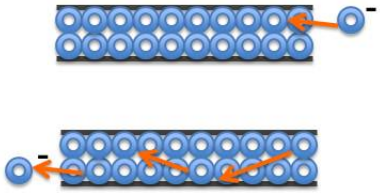


Electrical Circuits

It would take a long, long time for an electron to move from the battery, through a wire, and back to the battery. However, the wire is packed tightly with atoms. As an electron is pushed into the wire, it repels an electron in the wire.

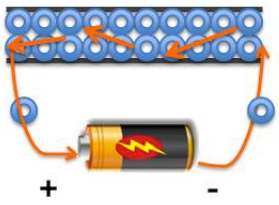
Electrical Circuits

That electron repels another electron. And that electron repels another electron. This happens very quickly because when one electron moves, those around it must move.



Electrical Circuits

This is how the electrical charge gets moved so quickly from one terminal on the battery, through a wire, to the other.



Electrical Circuits

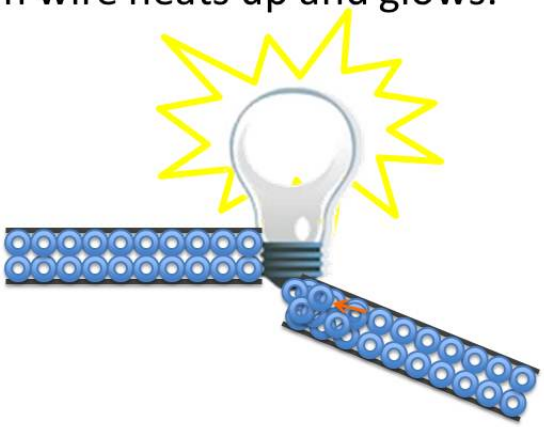
Usually, we want an electrical circuit to do something for us, such as light up a bulb.

Electrical Circuits

The current flows through the base of the light bulb, on its path back to the battery.

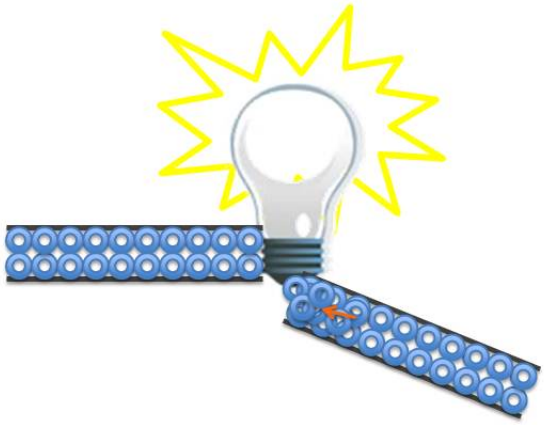
Electrical Circuits

The wire inside the light is especially thin and creates resistance to the flow of the current. The thin wire heats up and glows.



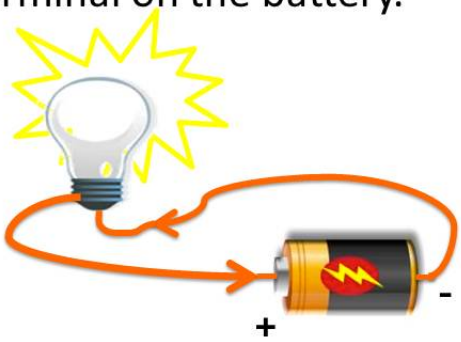
Electrical Circuits

The resistance causes heat, which makes the tiny wire inside the light bulb glow.



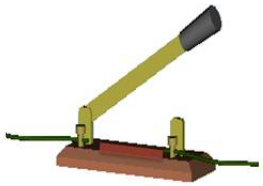
Electrical Circuits

The electrical current flows through the light bulb as the negative charge is attracted to the positive terminal on the battery.



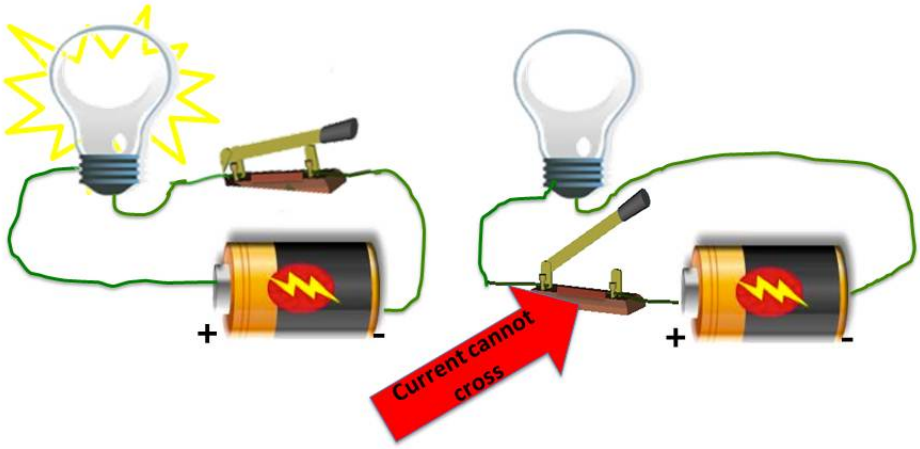
Switches

For convenience, we can insert a switch into a circuit. A switch breaks the circuit when it is open and completes the circuit when it is closed.



Switches

It does not matter where the switch is put in the circuit. If the switch opens after the bulb in the circuit, the current cannot flow.



4

Review

- An electrical current flows through a circuit, from one terminal of a battery to the other.
- If the circuit is broken, the current cannot flow.
- Remember that the current returns to the battery.

Electricity

Module B

Review of Atoms

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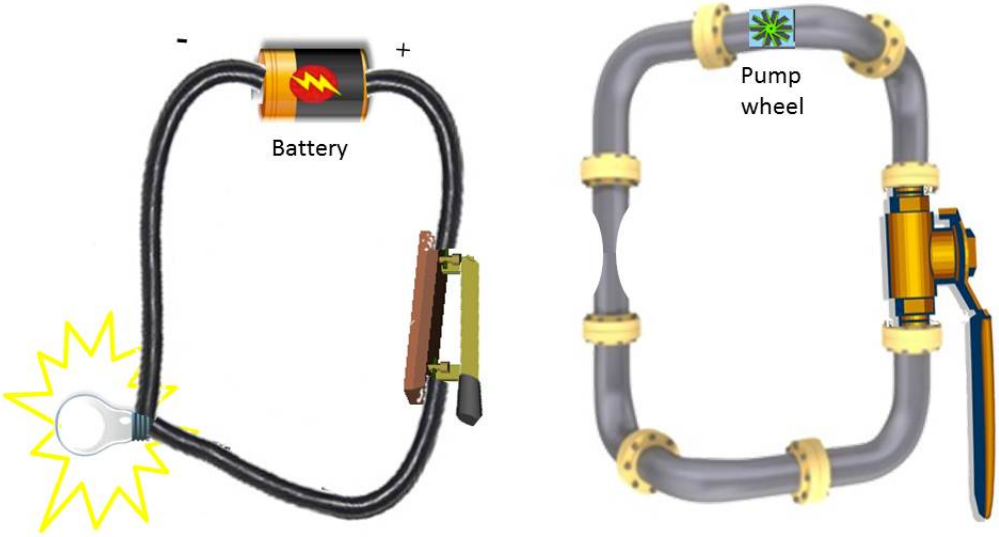
A Circuit is Like a Water Pipe



Electrical Circuits

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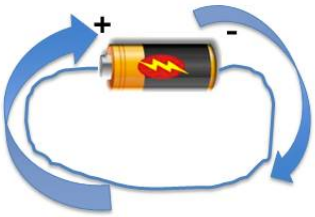

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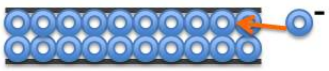

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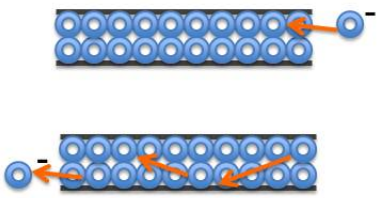
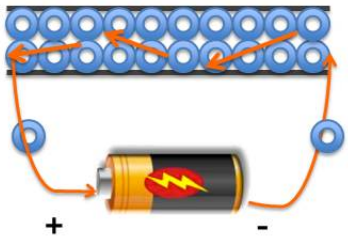


Electrical Circuits

This is how the electrical charge gets moved so quickly from one terminal on the battery, through a wire, to the other.



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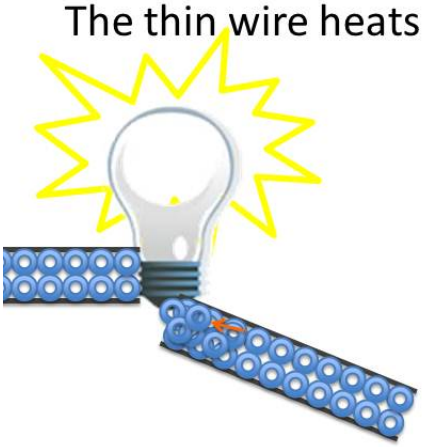

Electrical Circuits

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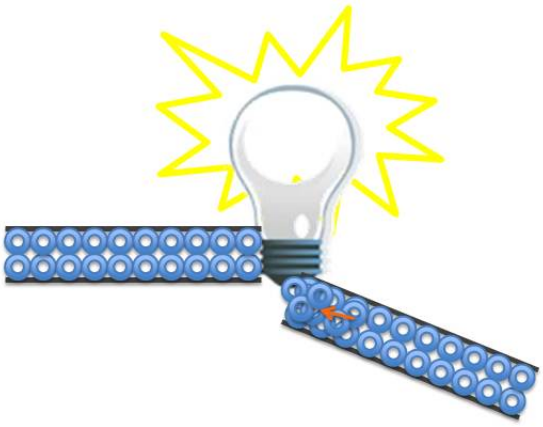
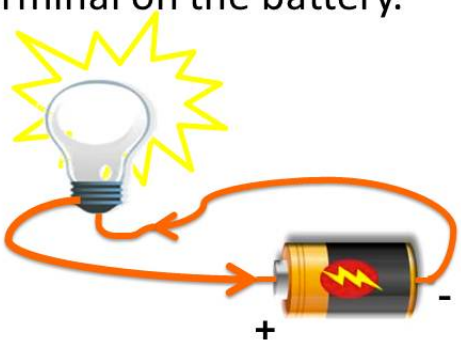


Electrical Circuits

The electrical current flows through the light bulb as the negative charge is attracted to the positive terminal on the battery.



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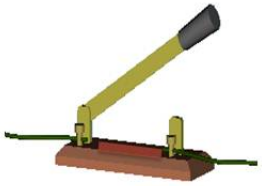

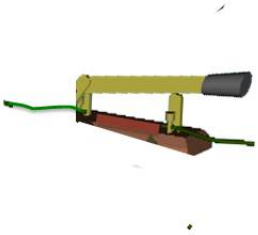

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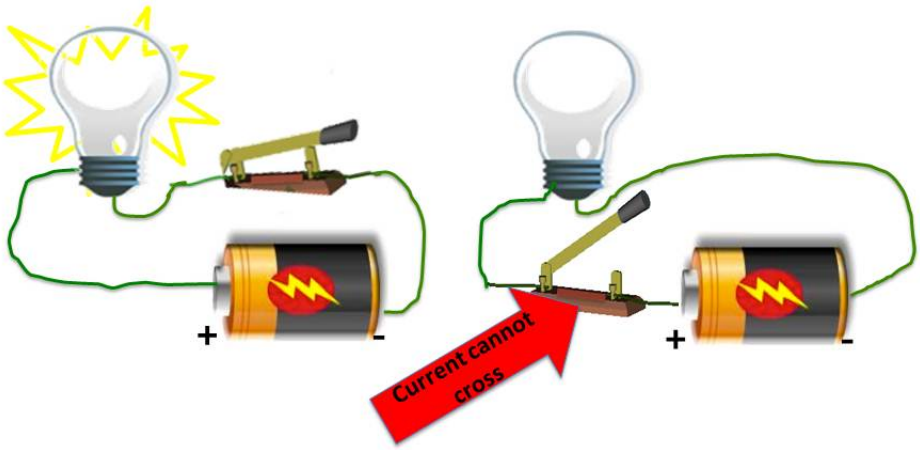
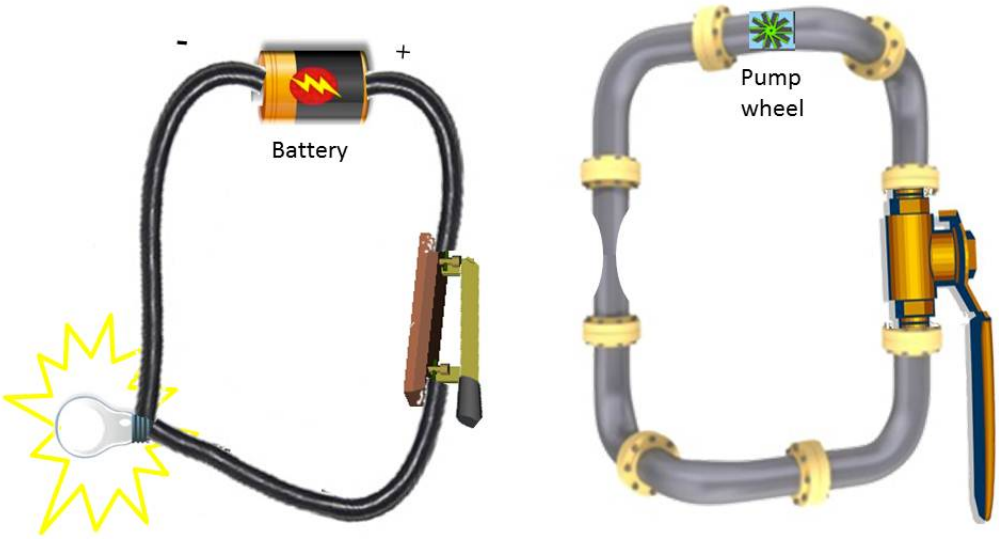


A Circuit is Like a Water Pipe



A Circuit is NOT like a Water Pipe

- A circuit is NOT exactly like a water hose and pump.
  - In a circuit, the charges are flowing, not water.

  - In a circuit, only the free electrons can move.
  - In a hose, all of the water moves.

  - In a circuit, the charges are repelling and attracting.
  - In a hose, the water pressure is pushing the water.

Electricity

Module C

Review of Atoms

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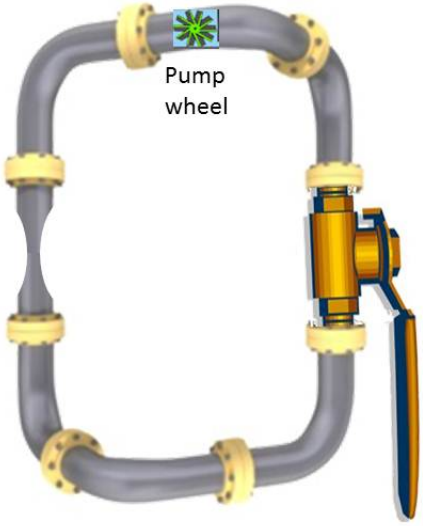
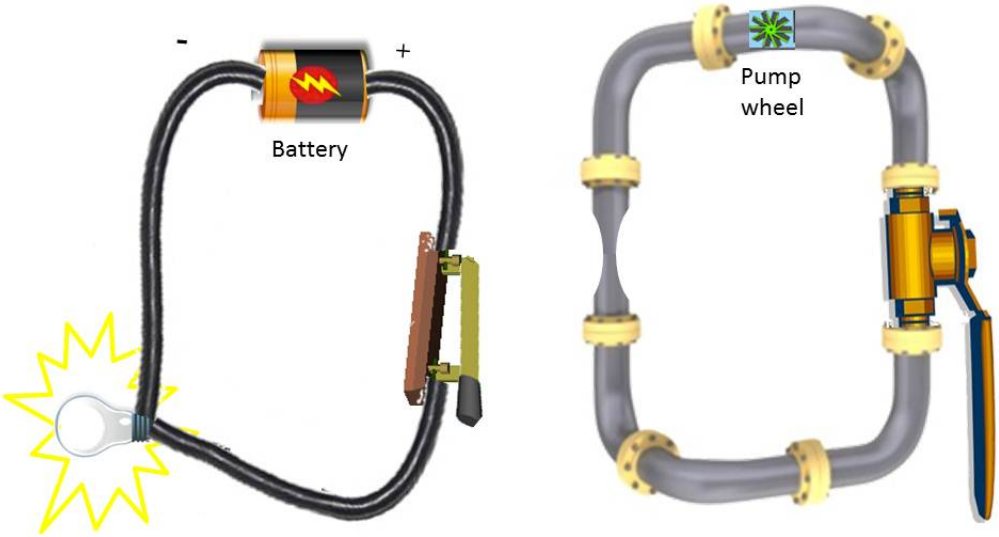
Like a Water Pipe and Pump

An electrical circuit is much like a water hose.

Pretend there is a pump, pushing and pulling water through a pipe.



A Circuit is Like a Water Pipe



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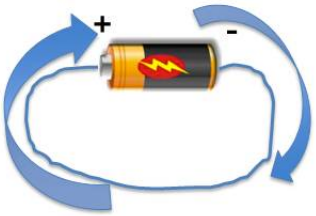
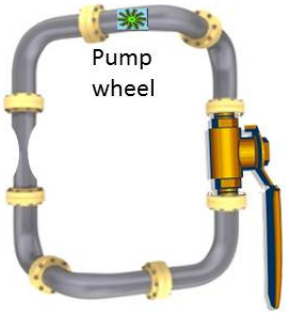


The battery is like the pump that pushes and pulls the water through the hose.



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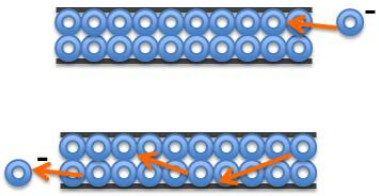
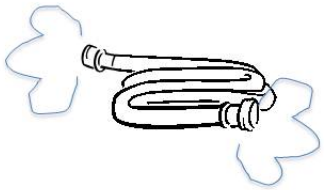
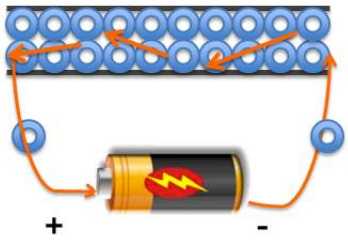


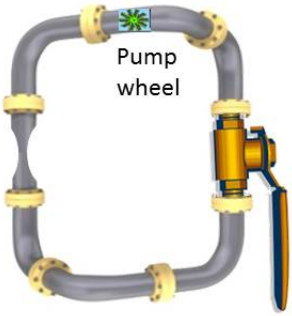


The pipe is full of water, so all of the water moves instantly and at the same time.

Electrical Circuits

This is how the electrical charge gets moved so quickly from one terminal on the battery, through a wire, to the other.





Electrical Circuits

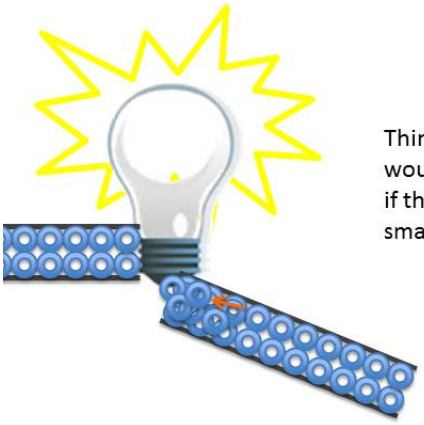
Usually, we want an electrical circuit to do something for us, such as light up a bulb.

Electrical Circuits

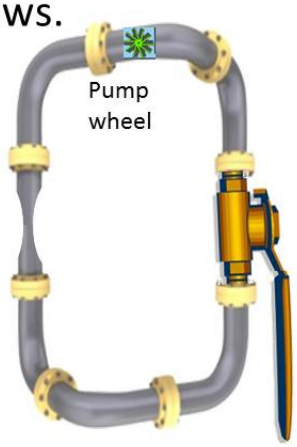
The current flows through the base of the light bulb, on its path back to the battery.

Electrical Circuits

The wire inside the light is especially thin and creates resistance to the flow of the current. The thin wire heats up and glows.

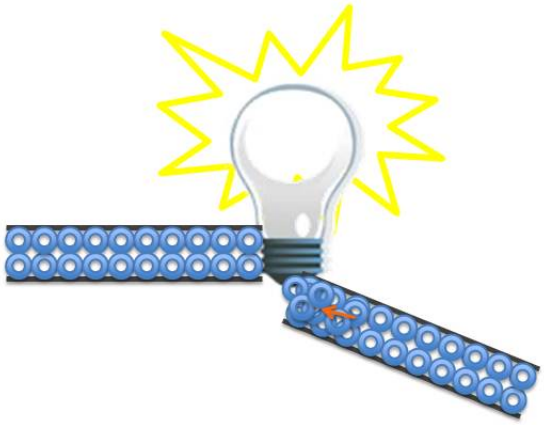


Think how hard you would have to pump if the hose was smaller in one place.



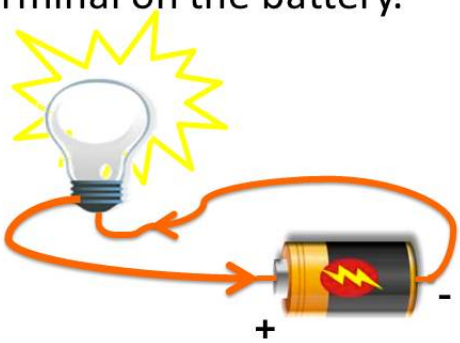
Electrical Circuits

The resistance causes heat, which makes the tiny wire inside the light bulb glow.



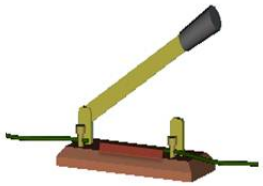
Electrical Circuits

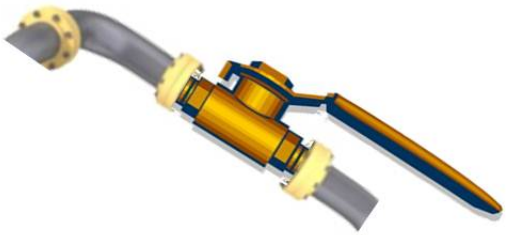
The electrical current flows through the light bulb as the negative charge is attracted to the positive terminal on the battery.



Switches

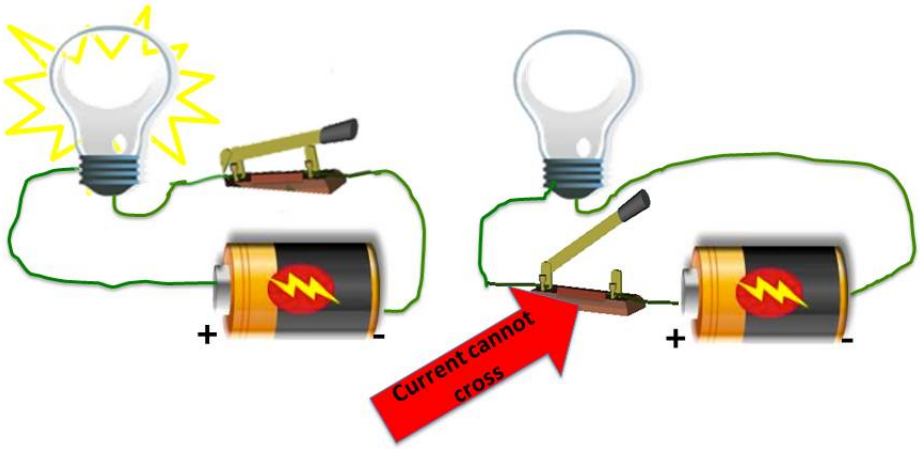
For convenience, we can insert a switch into a circuit. A switch breaks the circuit when it is open and completes the circuit when it is closed.



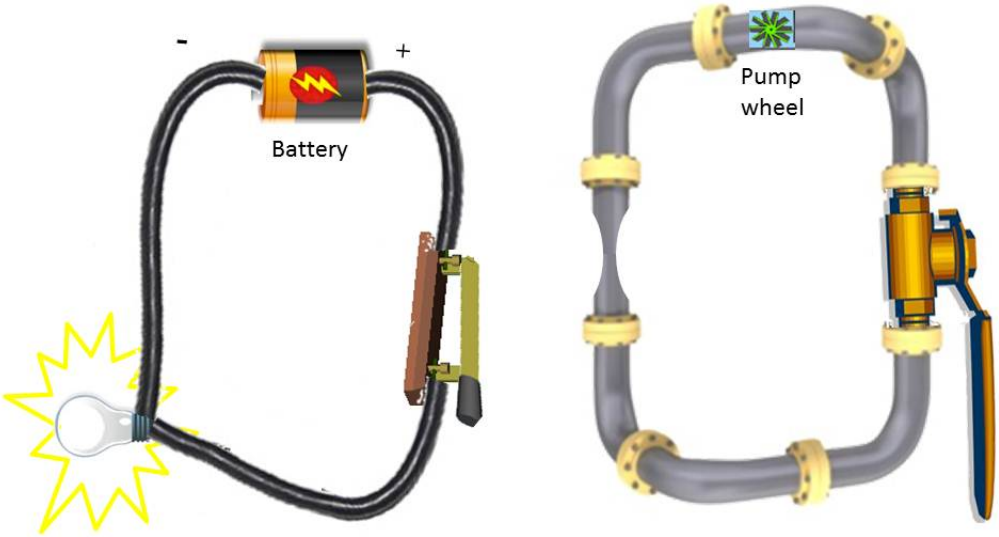


Switches

It does not matter where the switch is put in the circuit. If the switch opens after the bulb in the circuit, the current cannot flow.



A Circuit is Like a Water Pipe



A Circuit is NOT like a Water Hose

- A circuit is NOT exactly like a water pipe and pump.
  - In a circuit, the charges are flowing, not water.

  - In a circuit, only the outside electrons can move.
  - In a hose, all of the water move.

  - In a circuit, the charges are repelling and attracting.
  - In a hose, the water pressure is pushing the water.

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