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Enhancing Student Understanding Through Analogies in Teaching Science Concepts: Teacher and Faculty Perspectives

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ABSTRACT

Over 250 high school teachers and college instructors were asked to indicate their frequency of use of analogies in teaching biology or chemistry concepts and to provide their perspectives on the sources of these analogies and on their usefulness in teaching and learning science concepts. In addition, they were asked to provide examples of analogies they were using and to shed light on the characteristics of effective analogies. This paper describes the study, shares the results, and discusses the implications of the findings for students, instructors, curriculum and academic leaders. A case is made not only for including more analogies in the teaching and learning process, but also for using the type of language, phrases, and experiences today's students are familiar with and use on a daily basis. It concludes that analogical thinking and the use of analogy motivates learners, accelerates learning, and deepens their comprehension.

Keywords: Analogy, Metaphor and Simile, Critical thinking, Teaching and Learning, Deep Learning, Building on What students know, Accelerated Learning, Multimodal literacy, Science teaching.

Introduction

In several significant ways, analogy functions like (is analogous to) an enzyme within a chemical process. Just as an enzyme regulates and speeds up the chemical process, an analogy facilitates and shapes understanding and speeds up the process of comprehension. Like an enzyme that helps complete a chemical reaction that is prerequisite to other reactions, an analogy helps develop understanding that is needed for further understanding to be developed. For these and other key reasons, instructors every day in almost every classroom have been using analogies to get their points across to students and to increase their chances of success.

Analogy is defined as a similarity or likeness between things in some circumstances or effects, such as in function or position, when the things are otherwise dissimilar or entirely different (Morris, 1982). The intrinsic power of analogy and its use in communication is suggested by Root-Bernstein's observation (1999) that "It is not our senses that limit or liberate us, but our ability to illuminate the unknown by means of analogies to the known" (p. 142). Analogy is not discipline dependent, nor "learning style dependent" (Henry 2005). A clearer view of this concept for educators is to see it as a basic means of how the human brain works, and thus to embrace and capitalize on this tenet (Holyoak and Thagard, 1995; Hummel and Holyoak, 2002).

A recent study conducted by Noh, Ahn, and Kang (2013) searched for, and analyzed, the types of analogies in the chemistry domain of middle school science textbooks in South Korea:

> *A total of 235 analogies were found in 27 middle school science textbooks analyzed, which means that one analogy per 10 pages was used on average. The number of analogies found in each textbook varied considerably depending on both the publishing company and the chemistry domain. Functional analogies, verbal and pictorial analogies, analogies with abstract target and concrete analog, enriched analogies, everyday context analogies, student-centered analogies, and analogies with low systematic nature were frequently used. On presenting analogies in the textbooks, the term analogy and a discussion of the limitations of the analogies were rarely found. In comparison with the analogies in the science textbooks developed under the 7th National Curriculum, the frequency of analogies per page was*

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increased. There were positive changes in the aspects of representation, extent of mapping, and artificiality. No differences, however, were found in the patterns of the other aspects (p. 398).

Beyond textbook use of analogizing, the process is also seen in handouts and classroom worksheets at most educational levels. Whether these be grade school handouts of "pieces in a pie" showing the workings of fractions, or various educational tools offered at teaching or corporate workshops, the use of analogies is evident (Siuda 2011). For example, a current educational provider fostering process-oriented guided inquiry learning offers numerous activities/worksheets that can engage students in the learning of abstract science concepts. The activities focus on core concepts, work at deep understanding in their curricular materials, and work towards supporting higher-order thinking skills. One such activity supports the learning of quantum mechanics, using cartoon illustrations of living communities, complete with streets, building numbers, apartment units, and beds to correlate with electron distribution in atoms (https://pogil.org).

The same approach and strategy as analogy for understanding the periodic table of elements was used by Cherif, Adams, and Cannon (1994) in depicting the periodic chart as a small town with streets (the vertical columns) and avenues (the horizonal rows), neighborhoods (alkali metals, alkali earths, etc.), ethnicity (metals and non-metals), and two suburbs (the rare earths and actinides.) The use of analogy for understanding the periodic table of elements can also be seen as a means fostering a look at patterns/periodicity in the chemical world. Students would look at the patterns, and seek to portray them in analogous ways using tools that they know and can utilize successfully in the design of 'Periodic City' as the main focus in the learning of basic chemical principles (Siuda 2004).

Thus when teachers present a new scientific concept to students and "tack it on" to a relevant everyday concept, they are using what students already know to introduce them to what they don't yet know. In doing so, they are showing their students the relatedness of universal concepts; they are helping students align a new, perhaps difficult, scientific concept with past knowledge. Related experiences build upon each other. As the learner absorbs an idea, it becomes the underpinning for the next idea, and the cycle of learning continues. This fostering of continuity is well expressed in the eloquent statement of Robert Oppenheimer (1956): "Analogy is indeed an indispensable and inevitable tool for scientific progress-because we come to new things in science with what we have learned to think, and above all how we have learned to think about the relatedness of things" (129-30).

This article on the power of analogy in teaching scientific concepts is divided into three main parts. In the first section, we share the results of a research study that we conducted among biology teachers and instructors on the use of analogies in the classroom to not only present, but also fortify and augment, the learning of key concepts by diverse student populations. In the second part, we discuss the findings of the study, and provide examples and recommendations. We also share (in a third part) some ideas for the use of analogy that have been found to be effective in helping students understand new material.

Even if taken as a given that all students can learn, we also believe that they learn in different ways. Thus, through the concerted effort to utilize analogies in the classroom, to help teach crucial and likely difficult concepts, teachers can address the reality that we have students who learn at *different rates* and comprehend at *different levels*. The descriptors we use in the classroom to explain rate reductions in biochemical occurrences via the enzyme's presence, can be compared to the analogy's support of understanding across educational divides. Thus, one can analogize the analogy.

Students may learn a concept without the use of analogies, but may do so by taking longer to digest, master, and apply what they have learned. With the use of the right analogy, the rate of understanding of the new concept will likely be not only faster, but also be evidenced in more depth and breadth of conceptual understanding. We can think of analogy as a catalyst that lowers the requirement of cognitive ability to a level that students can safely engage in the learning process, thereby speeding up the process of understanding. Analogy can be the teaching aid that serves as a vehicle to help bridge the widely different ways students learn and view the world within and outside of them.

But what perspectives do teachers and faculty have about analogy and its use in their teaching of biology and chemistry concepts?

The Research Study

Methodology

Through questionnaires and in focus interviews, we solicited responses from biology teachers and educators at both high school and college levels. The questionnaire was short, specific, and dealt with only five main questions. Additional questions regarding personal information were also included as optional in the questionnaire. Originally, twelve questions were prepared as a draft for the questionnaire, but by the end of the process, only five questions survived the critical analysis and were found to be useful to the study (Table 1).

Table 1: The Five Main Questions In The Survey

	The Survey Questions
1	How often do you find yourself using analogies in the classroom in order to augment a specific biological idea/concept?
2	What are the most effective analogies that you have found in your years of teaching?
3	From your perspective, why do you think these particular analogies are so successful in helping you teach the intended biology concepts?
4	What sort of framework, model, and/or strategy do you usually use to integrate analogies into your teaching?
5	Describe in detail one of these analogies and how you have been using it in the classroom.

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Four hundred questionnaires were distributed through the Internet, accompanied by a short letter explaining the purpose of the study and its importance to the teaching of biology. Completed questionnaires were obtained from 258 participants, with a response rate of 66%. Furthermore, ten high school biology teachers and ten college biology instructors were selected for follow-up by means of in-depth interviews using similar questions to those in the questionnaire. Additional questions were raised during the interviews (Table 2).

Table 2: Additional Questions Raised During The Interviews

The Interview Questions	
1	When should analogies be used in teaching?
2	Should analogies be used even if we know from our own experience with the subject matter that the students will have no problem understanding the intended learning ideas or concepts?
3	Can analogies be used as an effective assessment technique for student understanding of the subject matter?

Participants' Profiles

The majority of respondents (67 %) were from college-level institutions, or taught at both the college and pre-college levels. Only 33% of respondents taught at just the pre-college level. Lastly, 62% of respondents were female, and 38 % were male. As shown in Table 3, the largest group of respondents (102 or 40 %) had between 11 to 20 years of teaching experience. Only 26 (10 %) of respondents had 30-40 years of teaching experience. Participants with 1 to 10 years of teaching experience accounted for 76 (29 %) of the 258 responses.

Table 3: Respondents' Years of Teaching Experience

Years of Teaching Experience of the Respondents (N=258)				
1 - 10 Years	**11 - 20 Years**	**29 - 30 Years**	**31 -40 Years**	**Total**
76	102	54	26	258
29 %	40 %	20 %	10 %	100 %

Data and Results of the Study

1. ***How often do you find yourself using analogies in the classroom in order to augment a specific biological and/or chemical idea/concept?***

As shown in Table 4, 180 respondents (70%) indicated that they have often, or very often, used analogy in teaching these concepts. Surprisingly however, 78 respondents (30%) indicated that they seldom use analogy in their teaching. The majority of respondents stated that most of the analogies they used were their own, and were spur-of-the-moment analogies that they used when they tried to help a student, or group of students, who were struggling to understand the intended leaning concept.

Table 4: How Often Respondents Use Analogy in Teaching Biology

Participants' Use of Analogy in Teaching Biology (N=258)					
Participant	**Very Often**	**Often**	**Seldom**	**Never**	**Total**
Female	42	72	45	0	159 (62%)
Male	24	42	33	0	99 (38%)
Total	66 (26%)	114 (44%)	78 (30%)	0	258 (100%)

Few respondents provided reasons or rationales for using analogies in teaching biology and/or chemistry, but a representative college-level respondent stated that:

> *When I am in the classroom, I use analogies on a daily basis, especially if I feel that the students need something they can relate to when trying to understand a difficult topic. Since all of the students had varying degrees of knowledge and different experiences to choose from, it made it difficult to present material in only one way. I would try to use analogies that the students could relate to, not always what some colleagues may have thought were the best explanations, but they worked for my students.*

A teacher from the high school level said:

> *I teach introductory biology to high school freshmen as well as the AP biology course to seniors, and without analogies (particularly for the more abstract concepts of molecular and cell biology), I truly doubt the majority of my students could master the material. Because of this, I use analogy almost continuously, not only to teach specific concepts, but also to assess student understanding. Requiring students to generate their own analogies is an excellent way to determine where misunderstandings occur.*

2. ***What are the most effective analogies that you have found in your years of teaching?***

While all the respondents answered this question, a few provided no examples of the most effective analogies that they have found to be successful in their teaching careers. The seven most mentioned topics for which respondents stated that they used analogies are the following: (1) protein synthesis, (2) enzymes, (3) the nervous system and how it functions, (4) the immune system and how it functions (T-cells and white blood cells and how they collaborate and function to protect the human body), (5) DNA structure and function, (6) photosynthesis, and (7) the difference between viral DNA and viral RNA. For example, a college instructor stated:

I use an electric cable as an analogy for the axon of the neuron; may be one of the most common, but it works. The socket is compared to the synapse and the electricity as the motor impulse coming to the effect or organ (the appliance). Then I explain the disease of multiple sclerosis as the damage to the cord which can cause the leakage of the electricity, and therefore the malfunction of the organ. Another analogy I use to explain the thermoregulation in the skin by vasodilatation is the old-fashioned radiator heaters through which hot water flows, dissipating heat.

Table 5 provides examples of the many analogies that respondents provided.

Table 5: Examples of the Analogies Provided

	Examples of Analogies
1	Using molded aluminum foil and gels to illustrate protein synthesis-especially transcription and translation-the one is described in detail in Ertmann's article (1997) "Protein Puzzle."
2	Comparing the allosteric interactions of enzymes (and other proteins) to the video special effects process of "morphing."
3	Comparing the decarbonation of soda to the release of CO2 during the alveolar gas exchange (and the opposite: the carbonation of soda at the cellular level).
4	Comparing the structure of DNA to a twisted ladder, epidermal tissue in plants to skin in a human, the hollow discus of grana to beta bread, etc.
5	Comparing the encoded information in DNA to a master set of blueprints for a building; the mRNA as a copy of one page of the blueprints; the tRNA as the construction workers; the amino acids as the bricks or building materials of the room; the rRNA as the construction site; and the finished polypeptide as the completed room.
6	Comparing the primary structure of proteins to a train (works for all polymers).
7	Comparing reversible reactions to a ball balancing on a "see-saw" (depending on which end you lift up, the ball will roll in the other direction).
8	Illustrating homologous chromosomes in meiosis with different size paper towel rolls: because the rolls are paper, they represent the genetic instructions for the same basic phenotype (homology); but because they are different in size, they are variations on the genotype for the phenotype (alleles).
9	Students don't understand that chromatids become chromosomes at the end of telophase II of meiosis, so I tell them to think of them like having a room with 10 pregnant women. If asked how many people are in the room, they would answer 10. However, the next day, all the babies have been born. Then they would answer 20 people. Chromatids become independent functional individuals after separation.
10	Monoecious, dioecious, and perfect flowers are traditionally compared to bedrooms-same house, separate bedrooms, different houses, or same house and same bedroom, respectively.
11	In studying plants, I discuss hay fever and the sensation one has when pollen enters the nose. This is nothing but plant sperm tickling the inside nasal passages. Students get a good visual picture from this.
12	Comparing the myosin molecules in skeletal muscle to golf clubs.
13	Equating a closed-circulatory system to an internal "ocean" and the movement of blood through it to the "tides."
14	In order to explain the neuron impulse, I use the analogy of a rope extending from me to the other side of town. On one side there are 50,000 men (positive ions) and 50,000 women (negative ions). On the other side of the line are 1,000 men and 1,000 women. I want a gallon of gas. I write the message out, but in order to deliver, the 1,000 men on one side of the line and 1,000 women on the other side of the line (rope), a man must cross the rope before he can pass on the note.
15	Comparing the organization of the nervous system as: peripheral neurons to phone wires; spinal cord to switchboard of a corporation; brainstem to departmental secretary (screening calls); limbic system to administrative assistant (screening calls for the CEO).
16	Mitosis was taught using an old ABT article using the hands/fingers as the genetic material. Again, this is a very good visual concept.
17	One day while trying to teach the basics of photosynthesis, I came up with a story to explain the key concepts I felt a freshman level class should know. The main theme of the story was Sally Sunlight was held hostage by Clyde Chlorophyll and how she was saved. The students were able to remember the story and the concepts that related to it.
18	The lab in which I teach (also lecture) has four doors. When I attempt to explain Starling's law of the capillaries I use the doors in my explanation: two of which enter the room and two of which exit.
19	I would teach passive and active transport using the explanation of falling down or tripping up a flight of stairs. Everyone has done this, and can relate to the concept.
20	Examples of natural selection; organisms being selected against, rather than selected for, examples of competitive exclusion and enzyme saturation.
21	One of my students recently used a Realtor effectively to tie together a theme for her seminar on the habitats of stoneflies. If the Realtor is selling a house, he/she would want to discuss how much space is available, the quality of that space, safety from gangs, local restaurants and quality of food, etc. It made an effective presentation.
22	I use desks in a room to help students understand carpels (walls) and locules (space/air we breathe) and ovules (desks).
23	The annulus of a fern bends back with the same sort of tension as a metal sheet. When it reaches a certain point, it will no longer bend in that direction and flings suddenly in the opposite direction.
24	This is one that students can relate to. Most students lately have never milked a cow so I don't use that analogy anymore for muscle milking action on venous return, although some can relate well to it.
25	One of my favorite analogies I found in a book for laymen about biology; it describes genes in a living cell like software programs stored in a computer hard drive. The programs can stay there doing nothing, except when you access them. Those which you don't access are still there with valuable information and function, but without accessing them, they are not doing anything.

Sources of Analogies Used in the Classroom

Over 65% of the participants provided information related to the sources of the analogies they use in the classroom. Participants who provided information stated they used more than one source for getting analogies applicable to their subject or topic of teaching. A common statement was that the most successful analogies for them were those they developed themselves, and/or read about and modified over the years (mentioned 84 times or 25%). The participants also mentioned successful analogies being those that they still remembered from their high school and college years (mentioned 74 times or 22%). Participants also mentioned analogies encountered in reading literature (mentioned 61 or 18%), those heard from colleagues, lectures, and conference and workshop presentations (mentioned 49 times or 15%), and analogies from textbooks used in courses and classes (mentioned 66 times or 20%).

As one participant stated:

> *The fact that I still remember those analogies after all these years, and I now use them in my classroom, is a clear indication that they are successful and powerful ones. They affected my understanding of the intended subjects and that is why I still use them; of course, I add my own seasoning to them to make them more current.*

Table 6 gives the sources of the analogies that were mentioned by the participants. Each participant mentioned at least two sources.

Table 6: Sources of Analogies Respondents Have Used in Their Classroom Teaching

Sources of Analogies (N=334)		**Times Mentioned**
1	Analogies they developed or read about and modified over the years	84 (25%)
2	Analogies their teachers used when respondents were students in high school or college.	74 (22%)
3	Analogies from textbooks used in courses and classes	66 (20%)
4	Analogies encountered in reading literature	61 (18%)
5	Analogies heard from colleagues, lectures, and conference and workshop presentations.	49 (15%)
Total		**334 (100%)**

3. ***From your perspective, why do you think these particular analogies are so successful in helping you teach the intended biology or chemistry concepts?***

Over 80 % of the respondents answered this question, and over half of them stated (directly or indirectly) that teaching complex, theoretical, and/or abstract topics is nearly impossible without the use of analogies. Biology and chemistry, as disciplines, are notorious for having many difficult to understand abstract topics; thus, with analogous reasoning, many attempting to teach these subject areas feel more inclined to be successful in the classroom with their students via the use of these teaching and learning 'tools'. Note that there is a recurring theme in most of the responses. Basically, professors believe that success is based on making the new material less threatening by connecting its main points to concepts that students already have a connection to. The following are examples of the reasons given for the success of analogies as teaching aids in the classroom.

1. *Analogies are successful because they typically are based on something with which students are familiar and which students can readily visualize. The analogies make a concept that may be foreign or "invisible" become visible. In general, those analogies that are based on something that students are quite familiar with in their everyday lives, or have encountered through the media, make for the most successful analogies. Typically, effective analogies are quite simple. One example might be that the triggering of an action potential is like filling a tipped bucket with water to the point of overflow. At some point, when one more drop of water is added, the bucket will flip and empty. Likewise, when the threshold of depolarization is reached, an action potential occurs.*
2. *(Analogies are great) because I relate them to the students' own "everyday" experiences for which they have some "feel."*
3. *If students can visualize something, then it is easier to relate it to something in their world.*
4. *They are memory devices that help students keep all the pictures together in regards to something that they cannot visualize. The analogy should be something they can visualize and/or readily understand.*
5. *In my meiosis chromatid example, it was a matter of convincing them that something could be counted differently once it had separated. They already understood that babies are counted differently after leaving the mother's womb.*
6. *When I was in the classroom on a daily basis, I used analogies every day. I felt that the students needed something they could relate to when trying to understand a difficult topic. Since the students had varying degrees of knowledge and different experiences to choose from, it made it difficult to present material in only one way. I would try to use analogies that the students could relate to; not always what some colleagues may have thought were the best explanation, but they worked for my students.*
7. *Most of the analogies involved visual images and/or situations that a student had experienced so they were able to draw on past knowledge.*
8. *I relate the reaction of the golgi body/dictyosome to Domino's pizza. Domino's doesn't make the cheese, pepperoni, sauce, etc., but instead recombines the ingredients to make a new final product (pizza), then*

packages it (box) and delivers it to where it is needed (hungry students). That is what the golgi body does: recombines chemicals, which are made in other locations, into new compounds, packages them into vesicles, and delivers them to where they are needed. I've thought about bringing in a pizza to make it dramatic. (Analogies) relate a foreign term/process to something they already know. Before I created this analogy, the students would respond on test questions that the golgi body makes the chemicals, etc., (if they remembered anything about it at all) but after the Domino's story they remembered everything—because they know about pizza delivery.

9. *(Analogies) provide a story base for the material and perhaps a little drama. People are much better at remembering a story than a small snippet of fact, so relating the information through a story or making an analogy with a story helps them retain the information.*
10. *I think any analogy ultimately works because it takes terms, ideas, phenomena, & relationships with which the students are already familiar, and places new terms, ideas, etc., within the context of those existing mental frameworks to allow them to create new links in their cognitive maps. The challenge becomes getting students to see the limitations of an analogy, so that they can then synthesize a new, accurate understanding that can stand on its own, independent of the analogy from which it was first built. This is one of the reasons why I sometimes have students make alternative analogies as an assessment activity.*

4. ***What sort of framework, model, and/or strategy do you usually use to integrate analogies into your teaching?***

Many instructors indicated that their analogies were really spontaneous, as a result of the particular classroom environment, the nature of the students in a given class, and the nature of the topic that was being taught. Sixteen respondents commented that they teach multiple sections of the same class, and they found themselves using either no analogy in some of them, or using different analogies for the same topic in different sections.

One thing that became clear from the study was that all the teachers who answered the survey had been using analogies in their classrooms. Also, 70% of participants indicated that they could not survive, or effectively communicate what they wanted to teach, without the use of analogies on a daily basis.

While the majority (77%) of the respondents indicated that analogies are spur-of-the-moment, 47% participants indicated directly or indirectly, that they have a framework or pre-arranged plan to introduce a certain analogy during teaching. When they plan their class curriculum and teaching strategies, they also plan what kind of analogies they want to use, when, and how.

One participant, familiar with the Glynn and Takahashi (1998) framework for integrating analogy into teaching, stated that (a) students need to be introduced to a target concept, (b) students need to be reminded of what they know of the analogy concept, (c) relevant features of the target and analogy should be identified, (d) similarities should be mapped, (e) where the analogy breaks down should be indicated, and (f) conclusions should be drawn. [Glynn's framework has also been cited and used in Paris's (1999) article "Biology by Analogy."]

5. ***Describe in detail one of these analogies and how you have been using it in the classroom.***

While less than 50% of the respondents provided us with a detailed description of one of their favorite analogies, a majority of them gave references to where they encountered effective analogies and from which they adapted some of the analogies they have been using. For example, one respondent referred us to the analogy developed by Ken Miller (1994) of Brown University, in which Miller uses computers to teach about the changes in genetic code. Another respondent referred to the same article, but in a different context, by mentioning the analogy of homologous chromosomes that Ken Miller learned from his high school teacher and described in his article "Using Analogies in Teaching Biology." This is how Miller (1994) himself described the analogy:

> *When I was struggling to learn the concept of homologous chromosomes, my high-school teacher compared human chromosomes to two sets of encyclopedias, one a World Book and the other an Americana. If you had both complete sets, he explained, you would have two "A" volumes, two "B" volumes, and two copies of the volumes for every other letter of the alphabet. Both "C" volumes, he pointed out, would have articles on copper, Columbus, and coral, but (and this was the key) they would not be the same articles. If you thought of each chromosome as a single volume, you could think of the homologous versions of Chromosome #3, maternal and paternal in origin, as being similar to the World Book and Americana versions of volume "C". All of a sudden, homologous chromosomes made complete sense. My teacher's analogy worked perfectly-it helped me to understand a difficult concept by comparing it with everyday objects with which I was already familiar. It is the perfect example of the proper use of analogy (p. 4).*

Interview Results

1. ***When should analogies be used in teaching?***

All twenty respondents who were interviewed agreed that analogy should be used whenever there is a need to help students understand difficult concepts, make sense of the unknown, or clarify misconceptions, and especially in teaching more abstract knowledge such as protein synthesis, photosynthesis, DNA replication, etc. Fourteen respondents added that teachers should also use analogies whenever they feel frustrated with the depth of the students' comprehension of concepts being taught. Furthermore, 9 participants wondered how someone can be an effective teacher or instructor without the use of analogy to convey the real meaning of a given principle and concept with no room for misconception and confusion. They just assumed analogy usage should be a given in the teaching and learning process.

2. ***Should analogies be used even if we know from our own experience with the subject matter that the students will have no problem understanding the intended learning ideas or concepts?***

The respondents were about equally divided in answering this question. Nine out of the twenty argued that analogies should only be used if the instructor is not able to convey an idea to the students, or when the students don't understand the intended ideas or concepts. They argued that the excessive use of analogies in the classroom, especially when not needed, may lead to misunderstandings among students, especially if the teacher is not experienced in the use of analogies or if the students' grasp of the analogies used is limited or incomplete-an argument that has also been raised in the literature (e.g., Paris 1999, Barrow and Milburn 1986).

However, the other eleven interviewees argued that it is the rights of the students to have instructors use analogies even when the students show no signs of difficulties in understanding the concepts presented. These interviewees felt that analogies should be used anyway, because they would reinforce student understanding of the concepts, help them relate prior experiences and familiar ideas to unfamiliar concepts, and also act as elements of entertainment to give the students a break from the normal routine of the classroom. Indeed, six participants from this group argued that analogies should be used all the time because they are essential tools in helping students in their cognitive development and creative thinking by relating the known to the unknown.

3. ***Can analogies be used as an effective assessment technique for student understanding of the subject matter?***

All twenty interviewees believed that analogies should be used as tools to evaluate student understanding of the subject matter. But only nine of the twenty indicated that they knew how to use analogy as an assessment tool, and were comfortable in using it as such. One participant stated, for example, that he often asked the students to explain the concept he had just taught them in a story format by using material that was familiar and available to them. He also said that by reading these stories, he could easily differentiate between students who had developed meaningful understanding of the material, those who didn't understand it, and those who understood it for the most part, but had a few misconceptions. Another participant stated that using analogy as an assessment tool enabled her also to find out which of her students had rich prior experiences and a high degree of imaginative and creative thinking abilities-skills that are vital for students' cognitive development and higher-order thinking skills.

Analysis, Discussion, and Recommendations

Even though the degree to which individual teachers use analogies varies, many teachers use analogies in their teaching on a regular basis. They do so because they believe that analogies have intrinsic power for explaining difficult concepts, making sense of the unknown, developing creative and critical thinking skills, enhancing thought processes, and relating new concepts to familiar ideas. This makes analogies an indispensable tool for effective teaching and learning, especially in the case of abstract concepts in STEM fields.

The sophistication of analogies and their use by teachers within societies, as well as among individuals, is influenced by various factors which include the following:

1. The nature of the language a given person uses. The way we use language fundamentally shapes our experience, thinking, and perceptions, and in turn affects how we use analogies as a mode of explanation (Fridland 2014).
2. The command of the language a given person uses. This is simply because the ways we use language create differences in how we teach and communicate and how students learn.
3. The prior experiences and exposure to the outside world of the person who uses the analogy.
4. The breadth of knowledge and depth of understanding that a given teacher possesses, not only in the discipline being taught, but also in other related disciplines.
5. The existing knowledge of the students about a given analogy their teacher uses.
6. The nature of the discipline being taught, whether it be mathematics, natural science, applied science, social science, language art, etc. For example, modern biology depends much on the understanding of basic chemistry, and thus understanding chemistry influences the use or sophistication of analogies intended to be used in teaching biology. The same can be said for geology, earth science, and geography, or for physics, astronomy, and mathematics.
7. How well the teachers and instructors know their students' academic and cognitive weaknesses and strengths, as well as what they are good at as an innate talent and/or work-experience born talent (Cherif, 2011; Cherif and Wideen, 1992).

Having a great breadth of knowledge and depth of understanding, an informative imagination, and skill in critical thinking are necessary ingredients for coming up with effective and relevant analogies for teaching concepts. People with limited knowledge and exposure to the outside world, and to their professional disciplines, usually find themselves using a limited number of analogies in communication, thinking process, and explanations of unknown or complex phenomena to others. Another important limiting factor is the learner's knowledge of the subject of the analogy. Thus, "students can be misled when their existing knowledge about the analogy is incomplete or fragmented" (Paris 1999, p. 38-39). Another limiting factor in the use of analogies is whether the topic is abstract or concrete. People use analogy more often in communicating abstract ideas and concepts than concrete ones. For example, scientists have been "escaping" to the realm of analogy every time there is no available knowledge to explain a new or unfamiliar concept. Also, they have been using analogy as a stimulus to imagination-- and they use imagination as a way of analogizing. They have found that analogy enriches imagination, and imagination enriches analogy in the thought process of problem-solving and discovery.

The excessive use of analogies can also lead to distractions within the learning process, especially if the teachers are not experienced enough in the use of analogies in teaching, and if they have a limited knowledge base about the analogies they use, and the topic(s) they intend to teach. Therefore, analogies should be used in moderation, and are likely to be more effective when used only in situations they are really needed. Students, on the other hand, should be given opportunities to develop and create analogies to express their understanding of the subject matter through any familiar means they choose. Such freedom and opportunities are essential for students' cognitive development and enhancement of their thought processes (Siuda 2004 & 2011).

Furthermore, students are more familiar than their teachers with the types of words, phrases, and expressions that students in their age range have been using. Thus, they might be able to come up with analogies that are more easily understood by their fellow students. For example, in a study conducted by Cherif et al. (2013; 2014), the authors surveyed 739 students to provide their own perspectives on why students fail courses and drop out of college. Motivation and study habits were mentioned most frequently as the root cause of student failure at the college level. When the same research team asked students face-to-face how faculty and academic leaders can help them become better motivated, they gave the following main suggestions: 1) communicate with them in the language they understand, 2) give them the tools they can use and technology with which they are familiar, 3) engage them in the teaching and learning processes, 4) give them responsibilities that lead to accountabilities, and 5) help them develop higher expectations for themselves and then demand these higher performances through educators truly engaged with their students. Thus analogies that use language, expressions, tools, etc., that students are familiar with will have more and better effect on student's comprehension than those that don't.
While most teachers use analogies at the spur of the moment, or when they discover that the students are failing to comprehend the subject matter, it would be more effective if the use of analogies were incorporated into the lesson plans including preparing the content, teaching, evaluation, and assessment. POGIL™ is such an educational endeavor, offering materials that can be used in the classroom in high school and college science courses. They offer many workshops as well, to help instill a newfound confidence in teachers to incorporate the tenets of multi modal literacy in the classroom (Kress 2003).

Even if teachers discover later that there is no need to use their analogies, such strategies enhance teachers' efficacy and self-confidence in teaching new concepts. After all, various psychologists, philosophers, and educators agree that, "the power of recognizing analogy is an excellent test of intelligence" (Root-Bernstein and Root-Bernstein 1999, p. 142). Because of this, analogies are not only good ways of teaching, but also good ways for assessing student learning and understanding of a target concept. For example, students could be asked to assess whether an analogy used in the class is accurate enough and how it can be modified to be more effective. Students could also be asked to come up with their own analogies to help explain a given concept and justify why this or that analogy could be better or more effective. Indeed, the use of analogy as an assessment tool is very effective in cementing the understanding of a given concept in the mind of the students. In doing so, analogy could help transform evaluation and assessment from a motivation killer to a motivation maker (Curwin 2014).

The question raised by many participants in this study, however, is: *How can teachers use analogies effectively and without developing misconceptions in the minds of their students?* One study participant, as well as Paris (1999) in his article "Biology by Analogy," stated that they found that the "Teaching with Analogy (TWA) Model" developed by Glynn *et al*. (1995) and Glynn and Takahashi (1998) provides a systematic way of presenting analogies to students and is very helpful in maximizing learning and minimizing misconceptions among students. Obviously much more is involved in this educational movement to multi modal literacy, but our focus in this paper is on shining a light on this growing means of teaching and learning of biological and chemical concepts. It is showcased to enlighten methods and to foster the "mind's eye" in the teaching and learning of biological and chemical concepts of varying degrees of abstraction.

Effective Analogies

The findings of researchers and the consensus of opinion suggest the following aspects of effective analogy use:

1. The most effective analogies use familiar knowledge and information to help learners understand less familiar or unknown circumstances. In addition, analogies that compare functional mechanisms rather than the structure of the two compared concepts, ideas, or objects have been found to be most effective. In other words, inherent in the effectiveness of analogies is their ability to allow the comprehension of functional rather than structural aspects of their entities.
2. Like a chain reaction in the chemical process, effective analogies are those which allow the user to apply many unrelated familiar ideas or concepts in explaining the unknown phenomenon, principle, concept, function, etc.
3. Effective analogies trigger a chain of thoughts in the mind of the listener.
4. Effective analogies are simple even though the analogy depends on the kind and complexity of knowledge the user and listener possess in common. Even a simple analogy can be complex if the user lacks the knowledge needed to understand the analogy itself. For example, a student who has never been in or seen a power planet and has no idea how electricity is generated is not going to understand the use of "The Power of the House" as an analogy for the functioning of the mitochondria in the living cell.
5. Effective analogies are those which our minds can translate into images or which trigger a chain of imaginative or creative thoughts.
6. Effective analogies do not require the use of more analogies to explain them.

7. As one of the participants explained, "Every effective analogy should do at least two things: first, illustrate a concept, and second, demonstrate how analogy works." And we can add as a third, it must trigger more thought about the learned concept.
8. However, since there is no perfect analogy, students must always be introduced to a target concept first before using the relevant analogy. Second, students need to be reminded of what they know of the analogy concept. Third relevant features of the target and analogy should be identified, similarities should be mapped, and where the analogy breaks down should be indicated. Finally, conclusions should be drawn after a given analogy is used to reinforce the understanding of the targeted concept.
9. Good analogy motivates learners and accelerates learning by facilitating and emphasizing the cognitive aspects of the new lesson. In doing so, it helps bring back the joy of learning, helps arouse curiosity, and induces an effective response from the learners.
10. Good analogy is a time saving cognitive device that helps to reduce the learning time required to master a concept.

In conclusion, a majority of the study participants agreed that analogy is a powerful teaching tool and that its use can definitely be an aid in teaching difficult material. There is agreement that the analogy's purpose is to make a difficult concept less difficult by comparing it with objects the student is familiar with. There is also agreement that in many cases it is difficult to really explain certain concepts in biology and chemistry without the use of analogies. Furthermore, 22% of the participants develop their own analogies and/or modify what they read to suit their students' needs and the learning environment. However, while the use of analogies as a teaching tool and teaching aid have been popular among many teachers and instructors, use of analogies as an assessment tool has not been widespread at the high school and college levels.

Another observation that emerged is that while modern learners are digitally advanced and use a lot of the new vocabularies, phrases, and expressions that are rooted in modern digital technology and communication, still many of the analogies that teachers use reflect earlier periods and experiences. This could be because the familiar analogies have proven effective, with no need to come up with new ones, or could be because the new vocabularies, phrases, and expressions rooted in digital technology and communication have not stimulated enough teachers and students to come up with a magnitude of new analogies to replace those that teachers have been using for many years. What is clear however is that learning builds upon learning, and analogy usage builds the imagination that leads to enhanced learning, learning that lasts a lifetime.

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Appendix

Framework for the Analysis of Analogies in Science Textbooks

(cited from Noh, Taehee, Ahn, Inyoung, and Kang, Sukjin (2013, p. 399))

Criteria	Type of analogies	Description
Nature of shared attributes	Structural	Shares similarities in external features and/or appearance only
	Functional	Shares similarities in functions and/or behaviors only
	Structural/Functional	Shares similarities in both external features/appearance and functions/behaviors
Representation	Verbal	Presented only in words
	Pictorial	Presented only in picture forms
	Verbal/Pictorial	Presented in both words and picture forms
Abstraction	Concrete→Concrete	Concrete target and concrete analog
	Abstract→Abstract	Abstract target and abstract analog
	Abstract→Concrete	Abstract target and concrete analog
	Simple	Does not include any statement of explaining the connection between analog and target
Extent of mapping	Enriched	Includes a statement of explaining the connection between analog and target
	Extended	Involves more than one analogs or several attributes of one analog to describe the target
Artificiality	Everyday context	use everyday situation(s) or object(s) with no change
	Artificial	Use everyday situation(s) or object(s) with some changes
Use of term 'analogy'	Used	includes terms like 'analogy', 'analogical' and so forth
	Not used	Does not include terms like 'analogy', 'analogical' and so forth
Systematicity	High	Includes the causality of the target
	Low	does not include the causality of the target
Description of limitation	Described	Includes the statements of the unshared features
	Not described	Does not include any statement of the unshared features
Students' participation	Student-centered	Requires students' active participation
	Teacher-centered	Does not require students' participation

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