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ABSTRACT

It is important to incorporate visual thinking into science instruction. Imagination and perception play vital roles in scientific inquiry. Metaphors, like perceptions, are drawn from common experiences and are a means to anchor scientists' thought processes in generating a pattern that bridges the gap between the seen and the unseen. Metaphors (visual and verbal) that relate to the emotional, aesthetic, and social forces of scientific inquiry are instrumental for teaching the epistemology of science. While metaphors compare implicitly, analogies compare explicitly the structure of two domains. Analogies can aid students in constructing new conscious models. A qualitative study in which 12 different analogies were used by six teachers engaged in teaching high school science, shows considerable success in learning by analogy. Instructional implications from one recent study on the use of analogies in high school chemistry include the need to develop a personal repertoire of useful analogies; the necessity of using analogies that students relate to; and the importance of explicitly mapping the attributes between the source and the target. Research has shown that without direction and training, students are not likely to use any of the general methods of visualization. (AEF)

Scientific Thinking Is In The Mind's Eye

Indrani Ganguly

Introduction

The National Science Education Standards (1993) recommended the inquiry approach of studying science. It was believed that the use of this approach will make science instruction consistent with the practice of science. Science can no longer be regarded as a body of unalterable truths, or of logical procedures, routinely and dispassionately applied to objective observations and numerical. Teaching authentic science presents science as a human enterprise, where the scientists' personal motivations, private intellectual activity, and their methods of solving problems are consolidated. Unfortunately, very few research studies (only about 10 of two hundred seventy five), have cast light on the above epistemology of science (Finley et al., 1992).

Visualization of scientific phenomena has been a key premise for thinking with several of the renowned scientists. Maxwell's visual-spatial thinking dominated his scientific accomplishments in the study of color and light. Faraday, driven by a strong imagination, created fiercely original mental models on electromagnetism and lines of force. Bohr's development of quantum theory, as well as Einstein's abstract scientific theories, would not exist had it not been for their fluid visual thinking. The habits of thinking used by the eminent scientists need to be taught to students through instructional interventions to attune them with the nature of science. Thus, authentic science teaching calls for the infusion of thinking skills instruction into daily lessons.

Mental models (Greeno, 1984) offer a systematic representation of the thinking pattern that is essential for a novice learner in transferring knowledge from a familiar to an unfamiliar domain. Mental models are built from personal interpretation of information. Hence, teachers need to be cognizant of the students' preconceptions of scientific ideas. Employing visual information to model a system's structure and inherent causal relationships is vital to invoking systematic thinking in students. However, the analogies, the mental models and any other visual information need not aim at a single deterministic immutable view. Rather, they can use a systematic thought pattern by which students learn the various facets of authentic science.

Visual thinking is a key tenet of scientific thinking. The rendition of science teaching needs to implicate the visual thinking strategies to insure a conceptual understanding of science that relates the natural world to the students' existing schema. Starting from the belief of Pestalozzi that all understanding is rooted in visual thinking, the theories of Arnheim (1986), Paivio (1986), and Gardner (1983) on mental imagery and spatial intelligence, reveal the effectiveness of teaching through representational aids in knowledge organization and integration. Mental models can provide a view of mind, meaning and method that could broaden the ways in which we think about science as inquiry.

Habits of Scientific Minds

Sir Peter Medawar, in Advice to a Young Scientist dismisses the notion that scientific discoveries are made by "just looking around."

> .....I think that Pasteur and Fontelle would have agreed that the mind must already be on the right wavelength ....that all such discoveries begin as covert hypotheses - that as imaginative preconceptions or expectations about the natural world and never merely by passive assimilation of the evidence of the senses.... The truth is not in nature to declare itself. Every discovery, every enlargement of the understanding begins as an imaginative preconception of what the truth might be.

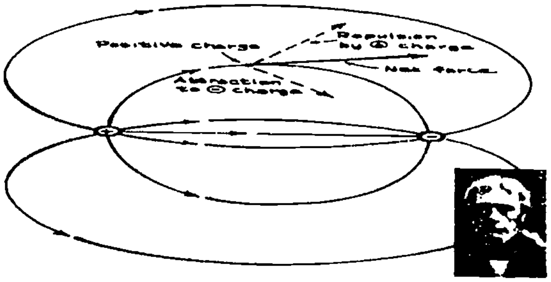
Science deals with aspects of life that we often cannot see literally. Hence imagination and perception play vital roles in pursuing this inquiry process. Scientists "see" by gathering data, measuring, making assumptions and forming tentative conclusions. Sometimes what can be perceived through our imagination cannot be at once perceived through human sensory organs. For instance, the wave nature and particle nature of light have been established through two distinct perspectives. Perception is an active process. We go out and get it. Individual perceptions are often tainted by cultural biases and expectations so much so that they fail to see beyond their realm of familiarity. Thus, the truth often gets lost because of our habitual propensity to place boundaries between ideas or concepts. In an effort to visualize something that is unseen, scientists have often resorted to metaphors to build up their thought processes.

Metaphors

Metaphors, like perceptions, are drawn from common experiences. Black (1977) called a metaphor the "tip of a submerged system of ideas." Often it is not clear what the notion of the metaphor includes and excludes. A metaphor incurs some sense of distance from ordinary language. The history of science is replete with the visions of those scientists who have reformulated problematic concepts through metaphors (Rothbart, 1984; Cole, 1985). For example, "light waves" do not undulate through space as water waves ripple over a still pond, an atom does not really "leap" from one quantum state to another, a "field" is not like a hay meadow, and electrons do not really travel around the atomic nucleus in circles any more than love produces literal heartaches. Metaphors are a means to anchor scientists' thought processes in generating a pattern that would thematically bridge the gap between the seen and the unseen. Jansen (1989) says, "metaphors are apprehended by the human eye, formed by the human tongue, tuned to the human ear and comprehended by the human brain." In different ages, scientists projected different perspectives in describing the same entity through their minds' eye. Their viewpoints were tainted by the sociocultural mores of their individual context and space. Thus, the metaphorical descriptors for the same natural world was once "a mother", a "world machine", synonymous with body/nature/matter/a female persona; "God's great pregnant automaton", in this century, an object that could be penetrated by nuclear bombs (as would pregnant phallus) and be overpowered. What something means to an individual belonging to a certain time and culture cannot be fully deciphered by those in different circumstances. Since metaphors are rooted in their experiential basis, they are a subjective proposition (Lakoff & Johnson, 1980). Moreover, since science is not a fixed system of non-negotiable theories and concepts, these multiple metaphorical perspectives of the scientists will do well to enable students acknowledge the true nature of science.

But the most unsettling thing is that the science that is dealt out in the classroom is far from what science is in its entirety. Teachers, anxious about covering the syllabus within a stipulated time frame, often introduce students to only one aspect of the scientific enterprise, namely the public science. Public science is a contingent plane of empirical facts and analytical relevance. The level of specificity and exactness that forms the key premise of public science is sufficient to debar any student to question any of those scientific propositions. Thus, a student who is not given a chance to reorder information, to alter existing categories, or to see new gestalts cannot be said to be participating in a learning activity. Holton (1973) emphasized that private science, which is a private struggle of scientists and their imaginative processes should be shared and kept in view in order to cohere and ignite scientific efforts. Factors such as emotional, aesthetic and social forces intrinsic to scientific inquiry need to be referred to when delivering science lessons. For instance, the British physicist, Michael Faraday, who earned the reputation of being the world's greatest experimenter, was thrown into a terrible discomfort when he could not visualize electric and magnetic forces in terms of "action at a distance." Faraday grew desperate over his inability to project something that would portray his imaginative vision of lines of force and then eventually came up with a graphical method for representing those forces (as shown in Figure 1).

Figure 1
Faraday and the Concept of Field



Faraday's imaginary lines of force associated with magnets and current-carrying wires existed in space whether there were other interacting bodies or not. As his research progressed, he increasingly rejected the idea of "action at a distance", as earlier proposed by Newton (Stockmayer & Treagust, 1994). The lines represented the force in two ways: the <u>direction</u> of the force at any point in space was along the lines, and the <u>strength</u> of the force was greatest where the lines were closely spaced. Faraday's graphical model of lines of forces was later termed as the "field" that permeated all space.

Metaphors (visual and verbal) that relate to the emotional, aesthetic and social forces of scientific inquiry are instrumental for teaching the epistemology of science. Students need to acknowledge that science is not all worked out, but is an open-ended inquiry process. Just as Faraday's visualization of electromagnetic effects shifted the focus from Newton's theory of action of a charge at a distance, scientific knowledge has forever been shifting focus from one concept/theory to the next; contradicting, modifying and charging ahead with newer convictions and glory. This does not mean that new theories have always replaced the old, or that one is right and the other is wrong. It just means that the new theory/perspective allows a better view of the physical phenomena - just like climbing a higher tower to see things better. Authentic science teaching permits flexibility and encourages students to think by means of visual aids like metaphors that allow accretion of knowledge by striking a thematic balance between the known and the unknown. Muscari (1988) however, cautions that both teachers and students of science must realize that once the insight has been achieved through metaphorical visualization, the hold on imagery must gradually be released.

Analogies

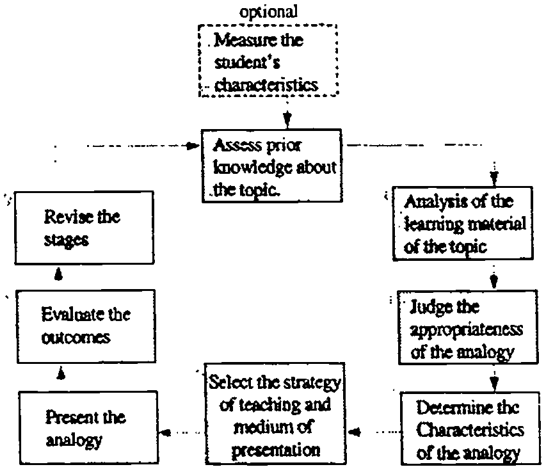
Both scientists in the academic societies and teachers in the classroom engage in acts of persuasion with words and visuals to create a new community of thought. When science teaching merely dwells on the factual description of events rather than an interpretive one, teaching becomes less persuasive in character. Some pupils may never discern the interpretive voice of the scientist and fail to see the more human aspects of the scientific epistemology. Using analogy is another way to lead the pupil's mind through an interpretive system. In the words of Faraday:

> You can hardly imagine how I am struggling to exert my poetical ideas just now for the discovery of analogies and remote figures respecting the earth, sun, and all sorts of things - for I think that is the true way (corrected by judgment) to work out a discovery (cited in Sutton, 1993; Michael Faraday, 1845, in a letter to C.F. Schoenbein).

Scientists have time and again used analogies to discover new laws or theories to explain natural phenomena. Huygens used water wave motion to understand light phenomena (Duit, 1991), Kepler developed his concept of planetary motion from the workings of a clock (Bronowski, 1973) and Maxwell mathematically explained Faraday's electric lines of force (Gee, 1978). These habits of scientific minds can be transferred to students of all levels to ensure that the learner's mental imagery is concrete. Once the student derives a clear idea of the base and target concepts, and their attributes, knowledge acquisition can proceed in a more systematic and meaningful pattern.

Teaching by analogy can be an effective approach in science. Analogies and metaphors are viewed as close relatives. While metaphors compare implicitly, analogies compare explicitly the structure of two domains. According to Brown (1993), students exhibit different conceptual levels: verbal-symbolic knowledge, conscious models, implicit models and core intuitions. Core intuitions are automatically employed and are domain general. These pose the maximum resistance to the acquisition of new knowledge. Analogies can aid in constructing new conscious models, enabling the refocusing of core intuitions. Zeitoun (1984) proposed the General Model of Analogy Teaching (GMAT) to promote accretion and tuning or schema evolution in learners (as shown in Figure 2).

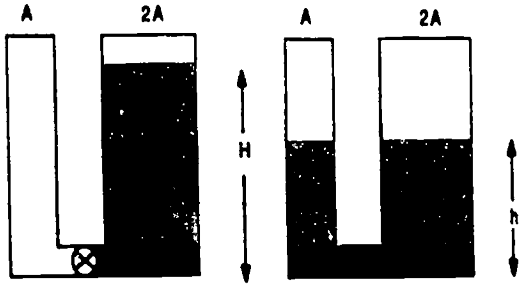
Figure 2
General Model of Analogy Teaching



To date there is little research evidence regarding teachers' use of analogies in the classroom (Treagust et al. 1989). However, the qualitative case study reported by Harrison and Treagust (1993), where 12 different analogies were used by six teachers engaged in teaching high school science, shows considerable success in learning by analogy. One such analog (visual illustration) was a pair of wheels rolling from a hard surface onto a soft surface to relate to the target concept of refraction of light from air into glass. The lesson consisted of the following stages: 1.Introduce the target concept to be learned, 2. Cue the student's memory to the analogous situation, 3. Identify the relevant features of the analog, 4. Map the similarities between the analog and the target concepts and 5. Identify the comparisons for which the analog breaks down. The analysis of interview data showed that the students' understanding of the concepts measured up to the expectations of the teacher, and the students derived immense satisfaction out of the lesson.

Another popular use of analogy is the use of fluid theory to explain the flow of electricity in physics. This model was first proposed in the eighteenth century and has stood the test of time. One such application of this water analog of electricity showed how a teacher utilized it in teaching college physics (Newburgh, 1993). In Figure 3, two cylinders of different volumes are connected by a stopcock. Water is contained in one cylinder only. In the next situation, the stopcock is opened and water is allowed to flow until the level of water is same in both cylinders. The target concept for the lesson was Kirchoff's potential law: when a capacitor having charge Q, capacitance C_1, and voltage V, is connected to a second capacitor with capacitance C_2, then the voltage across them will be the

Figure 3
Kirchoff's Law



same and the sum of their charges will be equal to the initial charge Q. It is clear from the water in the two cylinders having cross-section A and 2A, that the potential energy of water in the two cylinders would be different (M_L gh/2, and $M_R$gh/2). Since the masses of water in the two cylinders are in the ratio of 2:1, the potential energies will also be in the same ratio. Here the equality is not of potential energy but of potential energy per unit mass (gh/2).

The above analogy is an example of comparing and contrasting the two domains of base and target through semantic and structural correspondences. Thagard (1992) showed how the strengths of good analogies can be understood in terms of pragmatic, semantic and structural constraints. However, one needs to remember that in cross-domain analogies, there may be a tension created between the pragmatic constraint and the semantic and structural constraints. As in the above example, the notion of correspondence was the question of equality (not of potential energy, but of potential energy per unit mass). Further in the case of the analog water, there was one kind of mass only, as opposed to two kinds of charge. Hence, an analogy should not be mistaken for a one-to-one correspondence.

One recent study on the use of analogies in high school chemistry offers useful guidelines for science teachers (Thiele & Treagust, 1994). The implications of this research related to:
1. the need to develop a personal repertoire of useful analogies, 2. the necessity to select analogies that can relate to students' existing schema and 3. the importance of explicitly mapping the attributes between the source and the target. The teachers in this study varied considerably in the extent to which they mapped the similarities and dissimilarities between the target and the analog. Also, there was little evidence that the teachers preplanned their analogies. They all agreed that they mentally maintained a working repertoire of analogies which was built up on the basis of their experiences. With regard to the nature of the analogies used in the study, nineteen of the 45 analogies were pictorial. The fact that teacher generated analogies were drawn more frequently than those from students' experiences suggests that the students could be unfamiliar with some of the analogs and failed to make the correct connections. Since most teachers (84%), offered some explanation of the analogs, the original unfamiliarity among students was considerably reduced.

The above findings brings us directly into the question of what factors would make students more competent in making the visual connections required in an effort of analogy transfer. Students should be able to match learned visual structures to new information. Additionally, students should develop a habitual tendency to use visuals to understand abstractions in science, even if they are not prompted to do so. Research has shown that without direction and training students were not likely to use any of the general methods of visualization, such as analogies, concept maps or illustrations (Detterman, 1993; Sweller, 1990). Symbolic visualizations or mental models which do not resemble their referents but merely suggests structure can influence the learner's cognitive structuring skills (Novick, 1990; Schwartz, 1993). Cartesian graphs, Venn diagrams, trees and tables offer the pathway to reveal structural analogies to students. Schwartz (1993) conducted research on the above notion of visual formalism which persuaded students to make cognitive transfers from a known to an unknown domain, provided the topical information had the same structure. The study reported the following conclusions: 1. grade level emerged as a single determining factor that high school students (9-10 grades) were more likely to use path diagrams than middle school students (grade 7), 2. the latter used original visualizations or alphabetical indexing and 3. about 66% of the student generated visuals belonged to all three categories. These categories were: a) directional properties, b) one-to-many relations, and c) many-to-one relationships through letter indexing or path diagrams. Although the study had limited grade level range (7th, and 9th/10th graders), its insights are valuable for guiding future research in determining students' propensity to use visuals in effecting cognitive transfer.

A word of caution that must be mentioned here is that learners rarely come up with the same precise and compelling comparisons or analogies as mature adults. Students' conceptions usually have a limited range (Duit, 1991). The matter of relating something as akin to something else is contingent upon how quickly and effectively, based on ones experience, one can make a connection between the base and the target domain. Inquiry strategies in science teaching are intended to make students equal players. Probing the effectiveness of the relational structure through visual recourse gives teachers a chance to respect the open-endedness of science as a process, at the same time the science content is safeguarded so that the topic will also be covered. Teachers could meet with some difficulties here. For example, the metaphor uttered by a child (ten years old): "clouds are sponges" may not be the best simile in the world to relate their physical attributes together. It is up to the teacher to probe similarities as well as dissimilarities and to make the child aware of these at his/her level (in this case, formal operational). The degree to which a child remains committed to his comparison is termed by Black as the "emphasis" of the metaphor. How well the comparison communicates what the child believes about clouds is termed the "resonance" of the metaphor (cited in Flick, 1991). The teacher should not ignore the child's personal imagination and inquiry, for it may alienate the child from the scientific quest. It is true that the emphasis and the resonance of the metaphor could alter the contour of the lesson flow that would be necessary to summarize the topic, but it is still worth the trouble. Perhaps the non-conformity of the analogy or the metaphor to the concept at hand could be utilized to eradicate the misconceptions in the student's mind while reinforcing the current topic. Strategies of cognitive conflict (Driver & Erickson, 1983; Stavy, 1991) can remedy these misconceptions provided the students are able to "see" the conflict. The choice of anchoring examples is crucial in this approach. Care needs to be taken that analogical models are not pushed too far or employed in contexts for which they are inappropriate.

Conclusion

Science education researchers have long labored over various folds of science teaching such as, development of curricula, assessment techniques, instructional strategies and teacher education programs. But relative to these areas, they have expended little effort to determine what counts as "authentic science." Part of the problem could be that epistemic science scans three distinct positions of presuppositionism, falsificationism, and personal hedonism. All have been validated by scientists at different points in time, leaving educators in a quandary when making definitive statements on the true nature of science (Finley et al, 1992). However, if we are not imprisoned by prejudices such as, only a scant few of our students will embark on scientific careers and that science is not meant for the ordinary, then we stand a good chance of finding a clear direction.

Significant benefits can accrue both conceptually and practically if we treat scientific thinking not as a rarefied form of thought but as something that could be brought to the realm of the ordinary. It should be clear from my earlier citations that science presupposes some degree of visualization and imagination. If a student is unable to "see" what the concept is about or how to get closer to it by making parallel connections with something already known, the curriculum, problem-solving and evaluation strategies will be of no avail. The thinking of professional scientists who advance scientific thought and theories develops out of the intuitive scientific thinking of children (Kuhn, 1993). It is up to us to break loose from the deterministic approach of public science employed in classrooms and to introduce students to those aspects of private science that will help them understand the lie of the land.

It has been said (Parvanno, 1990):

> Children are born scientists. From the first ball they send flying to the ant they watch carrying a crumb, children use science's tools - enthusiasm, hypothesis, tests, conclusions - to uncover the world's mysteries. But somehow students seem to lose what came naturally.

I take the aforementioned statement as rhetoric and even an overstatement. I argue that to be able to imagine, explore, observe, reason, experiment and problem solve, one first needs to be emotionally bonded with the culture of the academic domain, and this is hardly possible if we give no place to private science in the classroom.

Scientific discoveries are not made just by looking around. Visualization is the mainstay for developing scientific thinking among learners. It should be noted that visualization refers to the cognitive functions of visual perception. It is not merely the physical raw material of vision, but images thoroughly processed by the cognitive powers of the brain (Arnheim, 1991). Metaphors, analogies and mental models are indispensable tools in visualizing abstract concepts of science. Metaphors and analogies have brought closer the two disparate fields of science and literature through the repeated attempts of scientists to place their abstractions in a public forum. Now it is time for us to realize where to put our emphasis on - get our students busy with problem solving or to empower them with the thinking skills of visualization, a mental crutch, that so tacitly adds a human dimension to the scientific quest.

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