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Getting to the Core Issues of Science Teaching: A Model-Based Approach to Science Instruction

The authors present analogies as useful instructional tools that improve students' and teachers' understanding by anchoring abstract concepts to concrete and familiar entities.

Introduction

Science teachers are responsible for guiding students through the process of learning and understanding science content. In order to carry out this charge, they need to present information in a manner that is congruent with the way students learn. Educational Psychologist Jerome Brunner summarized this issue when he wrote, "The task of teaching a subject to a child at any particular age is one of representing the structure of that subject in terms of the child's way of viewing things (Brunner, 1960)." Bruner stated that students must be able to "represent" phenomena at three distinct levels: the enactive, iconic, and symbolic (Brunner, 1966). The enactive level pertains to phenomena that can be observed. This is the world of experiences that includes what we learn about the world through our five senses. The iconic level refers to internal representations or models that students use to visualize phenomena. Finally, the symbolic level refers to the abstract scientific symbols, definitions, and formulas that are used to explain phenomena. According the Brunner, in order for students to truly understand a concept they need to have experience with it at all three levels.

Three Conceptual Levels of Scientific Understanding

Macroscopic Level

In order to specifically address the unique perspectives in chemistry and the physical sciences Johnstone (1991) proposes a parallel model that is amenable to these subjects. We refer to this model as the Three Conceptual Levels of Scientific Understanding. Johnstone's conceptual levels are parallel to Brunner's but he renames them the macroscopic, sub-microscopic and symbolic. The macroscopic level refers to phenomena that can be observed directly. At the macroscopic level students experience the phenomenon through demonstrations or hands-on activities. These types of observable demonstrations help students to build connections between experiences and science concepts (Bransford 2004; Bransford & Donovan, 2005).

Sub-microscopic / Particle Level

The sub-microscopic level refers to phenomena that occur at the level of molecules and atoms. In order to more accurately reflect the learning issues in chemistry,

Gabel (1999) asserts that this level be redefined as the particle level. The term particle is generic and can be applied to diverse species such as atoms, ions, or molecules. In order to accurately explain chemical phenomena students need to identify the relevant particles and describe the interactions between the particles.

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For example, research has revealed that students, at diverse developmental levels, have naïve or incomplete understandings of the process of burning (Driver, Squires, Rushworth, & Wood Robinson, 1994; Gabel, Monahan, MaKinster, & Stockton, 2001). Studies have shown that students recognize that oxygen is necessary but they frequently do not understand the role of oxygen in burning. Because students can not conceptualize how oxygen interacts at the particle level, they tend to envision burning as a process in which the starting material is destroyed.

At the macroscopic level, this is a reasonable conclusion based on common experiences such as burning a log or newspapers. The starting material breaks apart and the overall product, ash, appears to have less mass because of the loss of material in the form of smoke, carbon dioxide and other products. In reality, burning involves the addition of oxygen to materials which results in new products that have a greater cumulative mass than the starting material. However, students cannot observe how the particles of the starting material interact with oxygen. What they observe is the ash that looks and feels lighter than the original log or newspaper. Based on their macroscopic observations, it is relatively easy for students to develop the misconception that burning results in the destruction and consequent disappearance of matter.

In order to devise an accurate scientific explanation for burning or any other chemical phenomena, students need to be able to visualize the interactions between particles. Because they can not see these particles they need a tool for bridging the gap between their experiences and interactions at the particle level, models. By constructing their own models, the students can see, touch, and manipulate abstract information which help them develop a deeper understanding of the scientific concepts (Gilbert, 1991; Robinson, 2000; Gilbert & Ireton, 2003; Mclachlan, 2003; Hitt & Townsend, 2004).

Models and model building also helps teachers assess their students' knowledge and understanding. Research reveals that model-based instruction can be used to identify students' misconceptions about science content (Greca & Moreira, 2002; Bunce & Gabel, 2002; Taber, 2003) and the nature of scientific inquiries (Niaz, 2001; Justi & Gilbert, 2000). By assessing students' models, teachers can focus instruction on content that is the most difficult for the students to understand.

Because models are so critical to understanding concepts at the sub-microscopic/particle level, we propose that it be reconceived as the "modeling" level (Hitt & Townsend, 2004). We have two reasons for our proposal. First, because all scientific fields use models, in some form, there is a clear connection between the three conceptual levels of scientific understanding and diverse science subjects. This means the modeling concept is compatible with other scientific fields such as biology and meteorology.

Second, redefining the sub-microscopic / particle level aligns it with phenomena at significantly different scales. For example, a high school biology class can address concepts that range from processes at the molecular level, such as the replication of DNA, to ecosystems which encompass thousands of biotic and non-living variables. Students can not directly observe these concepts in the classroom but they can visualize them by creating models (Robinson, 2002; Mclachlan, 2003).

Symbolic Level

The symbolic level refers to scientific formulas, equations, and definitions. Students have the greatest difficulty understanding science content at the symbolic level because it is unfamiliar to them (Johnstone, 1991, Gabel, 1987; 1999; Hitt & Townsend, 2004). Unfortunately, science instructors tend to focus on the symbolic level exclusively which can result in students becoming disinterested and simply memorizing definitions and formulas (Gabel, 1993; 1999). Research on learning demonstrates that memorization is ineffective because it does not result in connections between concepts and the information is stored relatively briefly (Bransford, 2004; Bransford & Donovan, 2005).

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In this article we present an analogy, *Apple Activity*, designed to help science teachers and students reflect upon science instruction and learning at the three conceptual levels of scientific understanding. Analogies are useful instructional tools that improve individuals' understanding by anchoring abstract concepts to concrete and familiar entities (Lakoff & Johnson, 1980). This analogy provides a simple and familiar situation designed to help science teachers reflect on their students' perspectives. Too often science instructors, including the authors, teach science through traditional lectures that mainly address the symbolic and macroscopic levels. This approach is logical for science teachers who are experts but it can be confusing for students who are relative novices. The *Apple Activity* creates an analogy that helps science instructors to "see" the differences between experts and novices. After we introduce the *Apple Activity* we discuss how it connects the Three Conceptual Levels of Scientific Understanding to science content and effective teaching practices.

Activity Setting

This activity is presented in the form of a dialogue between Dr. Smith, the professor for a secondary science methods course, and his pre-service science teachers. We decided to present the activity as a vignette in an attempt to provide readers with a student's perspective. When we present this activity to teachers and students we assume the role of Dr. Smith.

Scenario

Dr. Smith starts class by stating, "Good morning class. I can tell you are eager to learn how to teach science. Let's start class with a simple concept." He then places a transparency on the overhead (Figure 1). "Now I want you to create a list of all the ideas that are relevant to this concept."

Figure 1: Grammatical symbols for a common object

After waiting a few moments Dr. Smith looks around the room and observes the confused expressions on his students' faces. He sardonically responds, "Oh this is ridiculous. Everyone in this class has seen this before! How can we even begin if you don't know such a basic concept?"

After waiting a bit longer, Dr. Smith decides to help the class out. "Okay class I know that it is early in the semester and you may need help in getting started so I will provide you with a different representation of the same concept." He replaces the first overhead with a second overhead (Figure 2).

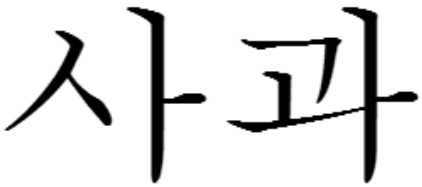

Figure 2: Second set of grammatical symbols for a common object

Dr. Smith asks, "Now can anyone give me some information about this concept?" The students continue to stare at the overhead and all the coaxing that Dr. Smith can muster fails to get responses from the class.

Dr. Smith finally concedes that the students are not familiar with the concept and that he must start at a more basic level. "Maybe I'm just introducing this problem the wrong way. Perhaps we need to approach this concept from a different perspective." He reaches into a brown grocery bag and distributes bright red apples to the class (Figure 3).

Figure 3 : Image of an apple

"What can you tell me about apples?" The students look at Dr. Smith wryly. "Now I want everyone to write down a list of observations that you can make for your apple." Initially the class is reluctant but with some encouragement they use their senses to investigate the apples.

After discussing the students' observations Dr. Smith distributes a collection of plastic apples (Figure 4). "These are plastic models of real apples that I purchased at a hobby store. Notice they look nearly identical to the real apple. I now want you to look at your list of observations for the real apple and cross out any observations that do not apply to the plastic model."

Figure 4: Image of a plastic model of an apple

Dr. Smith then leads a class discussion about the similarities and differences between the plastic models and the real apples. "Now class you probably noticed that the models have some similarities and some differences compared to real apples. This is because models are not exact replicas but are conceptual representations of the real phenomenon or target."

"You have probably seen many types of models such as physical models, computer models, mathematical models, and graphical models just to name a few. Despite their different appearances, all models have the common function of explaining and connecting concepts associated with the target. In our case we are using a simple physical model that addresses the concepts associated with apples. For example the idea that apples are 'red' is a concept that is built into our model."

"Now class does anyone have any difficulty relating this model to a real

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apple?" The students quietly indicate that they have no difficulty with this concept. "Good! Now we will examine two more models of apples." Using the overhead, Dr. Smith shows the class a two dimensional model of a red apple (Figure 5).

"Notice that this model is more abstract then the plastic model of the apple. In order to understand it you need to have a deeper understanding of apples and the concepts associated with apples. Now mark off all of the observations for the real apple that do not pertain to this model."

Figure 5 Colored two dimensional model of an apple

After the class discusses the common characteristics of the apple diagram and real apples, Dr. Smith places a simple black and white model of an apple on the overhead (Figure 6). He again instructs the students to mark off any observations of the real apple that do not apply to the new model.

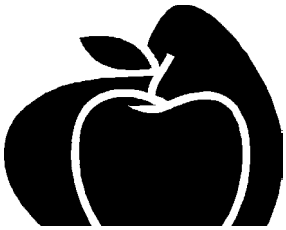

Figure 6: Two dimensional two-toned model of an apple

Finally, Dr. Smith is ready to share with the class the most abstract representation of an apple (Figure 7). "Now I want you to eliminate all of the attributes of the real apple that the word 'apple' lacks."

APPLE

Figure 7: Symbolic representation of an apple

Dr. Smith asks the class to share any observations they recorded for the real apple that apply to the word "apple." After another moment of silence Mr. Smith asks, "So none of you have any observations for this symbolic representation? Does that mean it has no meaning to you? Of course not! I bet the word apple conjures up a lot of images."

"The word 'apple' is a symbol or abstract representation of an apple. In fact no physical or conceptual information about an apple is observable. It is greatly simpler than a model and if you understand it you also have a firm understanding of the physical and diagrammatic models of an apple." Dr. Smith again shows the overheads for the word "apple" written in the unfamiliar languages. "I bet you can recall many images and ideas that are connected to these symbols or models." The students nod in agreement.

"Now I want to change the focus of our discussion. Imagine you are a student in a science class and one of the first things you are expected to learn is a definition, formula, or symbol. You are told that it is a basic concept and you must learn it because all future information will be built upon it. You are not familiar with this elementary concept so it might as well be in a foreign language. Can you imagine how you might feel at this moment?"

Dr. Smith walks over to the board and writes a formula for a chemical reaction (Figure 8). "Imagine that you are in Chemistry I and the topic is chemical reactions.

$$Cu\ (S) + 2AgNO_3(Aq) \rightarrow 2Ag\ (s) + Cu(NO_3)_2\ (aq)$$

Figure 8: Symbolic formula for the reaction of copper wire and silver nitrate solution

Based on what you have gleaned from the *Apple Activity* can you tell me how I could introduce this chemical reaction without using this relatively abstract formula?"

Discussion

Science teachers at all levels live for those "AHA" moments when the light goes on and their students grasp a concept. By sharing the *Apple Activity* with pre-service and inservice teachers and college faculty, we have observed many "Aha" moments. The *Apple Activity* provides educators at all levels with a fresh perspective on the problems their students face in their classes.

The *Apple Activity* also helps educators focus on the attributes of scientific models. Frequently science educators use a variety of models to

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explain phenomena but they do not explain the assumptions built into the models. Research in science education reveals that students maintain naïve conceptions about scientific models (Grosslight, Unger, Jay, & Smith, 1991). Without explicit reflection on the similarities and differences between the model and its target, students can internalize misconceptions. For example, we have used ball-and-stick models in order to teach high school students about molecular structures. The models were effective at teaching them the structure of molecules but the models also introduced misconceptions. After questioning our students, we found that many of them believed that chemical bonds were "sticks" or "beams" that held atoms together. These misconceptions could have been avoided by having our students explicitly reflect on the nature of models (Eichinger, 2005).

Another use of the *Apple Activity* is to help students reflect on the process of learning science. Many students find science intimidating because of all of the scientific jargon used to describe phenomena. The *Apple Activity* is a useful tool for addressing their apprehensions by informing them how the science content will be presented in class.

After completing the *Apple Activity* a chemistry instructor could tell her class, "The way we are going to approach chemistry this semester is analogous to the *Apple Activity*. The lab is like investigating the 'real apple' because you are making observations and inferences for real chemical reactions. Initially our lectures will be like examining the 'apple models' because we will be building molecular models and drawing cartoon-like images of molecules. Later, the lecture will be similar to identifying the 'word for apple' when we translate our observations and models into chemical symbols and formulas. By the end of this course you will have 'seen' chemical phenomena, created models in order to visualize the phenomena, translated your observations and models into a symbolic language, and used this scientific language to communicate with others."

Finally, the *Apple Activity* is a useful introduction to our main objective, improving classroom instruction by using the Three Conceptual Levels of Scientific Understanding (Johnstone, 1991; Gabel, 1999; Hitt & Townsend, 2004).

All three of the levels are interconnected and are essential for promoting student learning (Figure 9). Omitting a step disrupts conceptual learning and prevents students from making connections between real world phenomena, models, and scientific concepts.

The easiest level for students to understand is the macroscopic level which refers to observations derived from the five senses. In the *Apple Activity* this level equates to the students using their senses to observe the real apple.

The particle / modeling level consists of constructing models in order to visualize phenomena. They can be physical models, diagrams, verbal descriptions, computer models etc. Students can see and manipulate the models and effectively internalize scientific concepts. An example of this level in the *Apple Activity* would be the plastic apple and the apple diagrams.

The most abstract and difficult level for students to master is the symbolic which consists of the definitions, symbols, and formulas that describe phenomena. This level is difficult because it is comparable to learning a new language. The symbols used to describe the phenomenon are complete abstractions and provide no clues about the phenomenon. In the *Apple Activity*, the symbolic level is represented by the various words for apple.

In order to demonstrate the levels of scientific understanding in our science methods courses we select a concept such as a chemical reaction. For example we use the reaction listed in the scenario which involves a copper wire placed in a dilute solution of silver

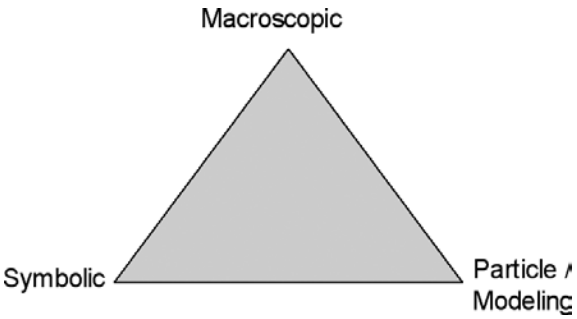

Figure 9: Three conceptual levels of scientific understanding

nitrate. We have students combine the reactants and then observe what happens at the macroscopic level. The copper wire and silver nitrate react to produce a silver precipitate and a bluish copper/nitrate complex (Figure 10).

Figure 10: Copper wire and silver nitrate reaction

First students observe the characteristics of a chemical reaction at the macroscopic level such as a color change, precipitate formation, and temperature changes. We then point out that all of the macroscopic characteristics of chemical reactions can also be observed during physical changes. For example: color changes occur when a dye is added to water, sugar precipitates out of tea when the tea becomes saturated, and temperature changes occur when water evaporates.

We emphasize that observations are only the first steps to understanding a phenomenon. By definition a chemical reaction is the breaking and forming of chemical bonds which results in the rearrangement of atoms and molecules. In order to visualize a chemical reaction students need to construct particle models (Figure 11). The model building process can produce diverse results due to the developmental levels of the students and the requirements of the course.

The critical requirements for a satisfactory model for a middle school science class or high school physical science course may be limited to balancing the equation and including the appropriate atoms and molecules (Figure 11a). After constructing the model the students can discuss how the particle model is different from the real chemical reaction. They can note differences such as the model of the Copper (II) nitrate molecule, $Cu(NO_3)_2$ and the model of Silver Nitrate $AgNO_3$ is a solid particle but in the actual chemical reaction the copper, silver and nitrate ions are aquated in solution, $2Ag^+ + 2NO_3^-$ and $Cu^{2+} + 2NO_3^-$. This process of comparing the model to its target helps the students recognize the limitations of their models and facilitates the development of more accurate scientific models (Figure 11b) (Eichinger, 2005).

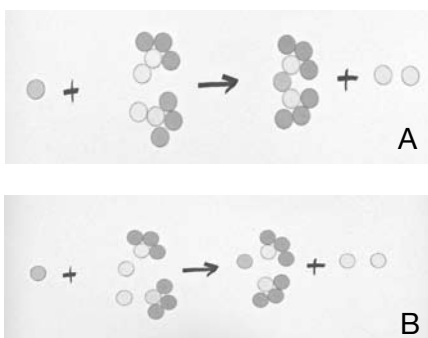

Figure 11: Student models for the reaction between solid copper and silver nitrate. (A) Lower level model that shows the Cu and Ag atoms covalently bonded to the NO_3 molecules. (B) Relatively more advanced model depicting the aqueous nature of the reaction. The interaction between Cu and Ag with NO_3 is not covalent but represents an interaction between opposite charges.

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In contrast, high school or college-level general chemistry students will be expected to produce more complex models and more detailed critiques of their models. For example, they may be required to discuss the structure or construct a model that accurately displays the blue species of copper $[Cu(H_2O)_6]^{2+}$ or create a model that represents a skeleton equation in which NO_3 is simply a spectator ion. After the model is constructed the process is the same as for younger students. The students compare and contrast their model to the target and adapt their model to meet the appropriate scientific explanation.

Regardless of the developmental level, we have found that when students construct models it helps them to visualize and communicate their ideas. Students, ranging from middle level to college-graduates, frequently tell us that this is the first time that they can "see" what occurs during a chemical reaction.

Finally, the students create a symbolic formula in order to describe a chemical reaction (Figure 6). The formula for a chemical reaction is a compilation of symbols that do not resemble the actual reactants and

products. Because the terms in the formula are not intuitive and composed of symbols we prefer to designate the chemical formula as a symbolic representation. In our experiences we have discovered that some students and educators prefer to interpret the formula as a model or envision it as a hybrid of symbols and a model. In any case, the chemical formula is more abstract than the particle model and discrepancies over the nature of a chemical formula can engage students and educators in interesting scientific discussions.

Final Thoughts

The three conceptual levels of scientific understanding can be used to improve science instruction by aligning it with the way students learn science. In order to convince secondary inservice and preservice teachers of the efficacy of this model we utilize the *Apple Activity*. The activity has received positive feedback from both groups. Based on our experiences, we believe that it can also be used with inservice and pre-service teachers at the elementary to middle school levels. When science instruction is based on the three levels of scientific understanding it becomes compatible with the way students learn. As a result science teachers can help their students master the "core" ideas in science.

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