Theory-Based Teaching Strategies for Conceptual Understanding of Chemistry

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Abstract

The Information Processing Model and the Social Constructivist Theory provide a basis for modifying teaching strategies traditionally used in introductory chemistry courses. Theory-based strategies that have potential for improving students' conceptual understanding of chemistry include: Integrating the macroscopic, particulate and symbolic ways of representing matter whenever appropriate; using ConcepTests during lectures; utilizing the Learning Cycle approach for laboratory instruction, and using Problem-Based-Learning.

Did you know that many college students think that when your fingernails grow, this is considered to be a physical rather than a chemical change (39%), and that when dry ice changes to a vapor, this is a chemical rather than a physical change (33%)? And when wood burns, this is considered a decomposition reaction (38%)? And given a group of equations representing chemical reactions that includes ones that show oxygen combining with both carbon and methane, only 33% think that both equations represent burning?

These data were obtained from 270 prospective elementary teachers who were enrolled in an *Introduction to Scientific Inquiry* course after 15 hours of instruction on the states of matter; differences between elements, compounds and mixtures; heterogeneous mixtures and solutions; and simple reactions. All were discussed on the macroscopic, particulate, and symbolic levels, and all were included in laboratory activities that included the manipulation of models. Ninety nine percent of the students had a one year course in high school chemistry. The topics included were those that elementary teachers are expected to teach in kindergarten to sixth grade on the macroscopic level according to the *National Science Education Standards* (National Research Council, 1996) in the United States.

Perhaps the above results should not be surprising. They corroborate the research of Bodner (1987) who found that some students enrolled in the chemistry graduate program at Purdue University (and who had completed undergraduate chemistry majors at other institutions) thought that the gas found in the bubbles of boiling water were hydrogen and oxygen rather than water vapor. This research replicated part of the study of Osborne and Cosgrove (1983) who tested children from ages 12 to 17 and found similar results.

Doctoral students enrolled in a science education research seminar at Indiana University also had misconceptions about fundamental chemistry concepts. When studying research on science misconceptions, students were asked whether toast burned or decomposed when it was overheated in a toaster. Most thought that it burned. The evidence cited was the blackness that occurred. In the ensuing discussion, questions were asked about the sustainability of the reaction, whether the toast emitted heat and light while reacting, what the composition of black material produced was, and if the black material burned, what the appearance of the product of the burning would look like. Some students said that they had never looked at toast while it was in the toaster and were not convinced of the reaction type until after they did so.

Unfortunately these kinds of discussions usually do not take place in many chemistry courses. Instead, chemistry is taught on the symbolic level using materials that are unfamiliar to students. Problem-solving frequently involves using a methodology that is also unfamiliar called the factor-label method or dimensional analysis. Would teaching chemistry using more familiar materials and processes increase students' interest in chemistry?

Chemistry is a very complex subject, more complicated than some instructors realize. As Johnstone (1991) illustrated using a triangle, matter can be represented on three different levels: the macroscopic, the particulate, and the symbolic. Examination of most introductory high school and college chemistry texts indicates that there is little effort (although in recent years it is improving) to show the

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inter-relationships among the three levels even though there is evidence that students do not see the relationships. For example, Yarroch (1985) showed that only 50% of the high school students he interviewed who could balance equations correctly (symbolic level), could represent the particles correctly. At the college level, Sawrey (1990) showed that the percentage of students who were able to solve problems about gases (symbolic level), was significantly higher than students who could represent what was happening at the particle level.

That students relate the symbolic and the particle levels to the phenomena at hand is even more uncommon. Most of the reactions included in introductory chemistry texts do not relate chemistry to everyday chemicals and common chemical/physical reactions. Even after an introductory high school chemistry course, many students do not know that burning normally involves the union of oxygen with a substance, or that decomposition doesn't necessarily produce a bad odor. Instead of using common materials in laboratory activities and in assigned problems, textbooks use chemicals such as sodium hydroxide or silver nitrate, substances familiar to chemists but not to students. If students are so unfamiliar with a substance that they cannot describe the physical properties of the material, they will not see the relationship between the phenomena level and the other two levels. In reality, the phenomena level is really symbolic, the unfamiliar name being the symbol. This adds memory overload to the learning situation. The additional barrier prevents students from acquiring a more comprehensive conceptual view of chemistry in which the symbolic, particulate, and phenomena representations of chemistry are fully integrated. Phelps (1996) found that many excellent college students were initially resistant to studying chemistry on the macroscopic level using common everyday phenomena because they had been conditioned into thinking that problem solving was the most important aspect of learning chemistry. Perhaps this provides an explanation for the graduate students who thought that the bubbles in boiling water were hydrogen and oxygen, something that was never discussed in class because it did not lend itself to problem solving. or the instructor thought that it had been learned previously.

Models/Theories of Learning

Two current theories/models of learning provide some insight about understanding why students find learning chemistry difficult, and also provide the basis for making recommendations about changing instruction to make it more meaningful. The information processing model (Cowley, 1998) helps us understand how information gets stored in the mind. The social constructivist theory of learning as described by Driver and Oldham (1986) examines factors that enable or enhance the transfer of knowledge to long-term memory.

Information Processing Model

Simply stated, the information processing model proposes that all information that is stored in the mind is first sensed by the individual. Some of this information goes into short-term memory (of limited capacity), and under the right conditions, is stored in long-term memory. The goal of education is for individuals to build a complex network of interconnected concepts in long term memory that can be drawn upon for problem solving and other tasks. When a fact/concept enters long-term memory, it can enlarge an existing network or may be an isolated fact. It is thought that novices have limited networks, whereas experts in a field have extended networks. One reason why analogies are effective in learning is because if a person sees the similarity between the analogy and the phenomena being compared, it will extend the network, and comparisons can be made between the analog and the new concept.

These thought patterns in long-term memory can be represented by concept-maps. An excellent example is shown by Herron (1996) in his concept map on an ideal gas. The map contains three distinct parts, each of which could be taught separately and never linked. The central part consists of concepts such as volume, pressure, and temperature. The section to the right of this contains concepts such as molecules, velocity, point masses, randomly, kinetic energy, etc., and to the left, the third part is a collection of concepts such as pure, mixture, nonreactive, reactive, at equilibrium, etc. At some point in the instruction, it would be useful for students to see the relationship between the three sections.

The same can be said about teaching chemistry using phenomena, the particulate, and the symbolic levels. Many times these are taught separately, and students form powerful individual networks on each level. However, they do not see the connections among the levels.

In some cases, disassociating the levels is very appropriate. For example, when teaching elementary-aged children, the preferred mode of teaching is at the macroscopic level. Research shows that below the sixth grade, most children do not understand the particulate and symbolic levels (Berkheimer & Blakeslee, 1988). At the high school level, teaching all three levels is appropriate, and although it is not necessary to do this at all times, a sufficient number of linkages need to be made to help students make the connections. Textbooks could eliminate the chapter on the kinetic molecular theory (as some have done), and incorporate the theory into other chapters of the text where the kinetic molecular theory is in an appropriate position to show how theory provides an explanation of phenomena. And as indicated earlier, why not build chemistry instruction around common, everyday materials and experiences that students have had? Using these networks that already exist in their long-term memories eliminates the need for building new networks of less familiar materials, and creating a new mathematics (dimensional analysis) that appears unrelated to the arithmetic students have learned in elementary school.

Social Constructivist Theory

Another model on how students learn is described by the social constructivist model described by Driver and Oldham (1986). If students interact with teachers or other students, are exposed to conflict situations through discrepant events, and they reflect on the new events in terms of past learning, they construct new understanding. This is accomplished through restructuring concepts already in long-term memory and forming new linkages. The Learning Cycle Approach, introduced in the Science Curriculum Improvement Study (SCIS) program (1971) for elementary science instruction in 60s and still in use today, is based on this model. Instruction is delivered in three different stages. During the Exploration stage students informally investigate science concepts by “messing around”. The objects that they explore are carefully selected by the curriculum writers so that cognitive conflict occurs. This is followed by the Invention stage in which the concept explored is more formally introduced by the teacher. In the final Application stage, children apply this new knowledge to other contexts.

The use of the Learning Cycle in chemistry instruction was introduced by Abraham and Renner (1986) in the early 1980s. By using this approach, students confront their prior thinking, and interact with their teacher and other students in clarifying their ideas. Traditional lectures are much shorter and are modified to focus on conceptual understanding rather than algorithmic problem-solving and the derivation of equations. In the Application stage, students have an opportunity to extend their conceptual understanding to new situations and contexts.

In the present decade, chemistry educators have begun to develop other teaching strategies based on the social contructivist model. These include modifying lectures, and using more inquiry laboratory approaches.

Strategies Based on Learning Theory

No one teaching strategy is appropriate for every instructor or student, nor for every type of learning environment. Sometimes fiscal restrictions, demanding that instruction be delivered to large groups of students, limits the teaching strategies that can be used effectively. However, even in these situations, more interactive teaching strategies exist that can be incorporated into instruction that might help students build larger conceptual networks, and hence improve achievement. The strategies described in the next section are theory-based and have been incorporated by the author and others in chemistry instruction. More details about some of these strategies are given in an excellent website being developed by the National Institute of Science Education (NISE) in the United States for instructors of college-level introductory science courses. The College Level One Team website (http://www.wcer.edu/nise/cl1) contains descriptions of ten classroom assessment techniques (CATs) which are written by science instructors who have used the technique. In addition to the description, references and instruments that can be used to assess the effectiveness of each technique, are given.

Integrating the Phenomena, Particulate, and Symbolic Levels

Students frequently do not see the relationship between the phenomenon that they observed in a laboratory activity, the explanation for what they observe in terms of what is occurring on the molecular level, and the relationship of the phenomenon and the particles to the symbolic calculations they have made in writing up the laboratory report. This probably accounts for the very low percentage (3%) of college chemistry students who were able to answer a question on the General Chemistry Conceptual

Examination (American Chemical Society, 1996) that asked students to determine approximately how much water was decomposed when 50 mL of hydrogen was produced.

If conceptual understanding is the objective of chemistry instruction, then students must have the opportunity of linking the macroscopic, particulate and symbolic levels of representing matter. For example, after students have seen the electrolysis of water in the laboratory activity or as a demonstration, the following additional problems could be presented:

a. How could the electrolysis of water experiment/demonstration be modified to measure the volume of water that was decomposed to produce the volume of hydrogen and oxygen that was observed?

b. Given that 20 mL of hydrogen was formed in the electrolysis of water, calculate the volume of water that decomposed. Assume that the density of water is 1.0 g/mL and that the gas at STP. Assume that the hydrogen is pure.

c. In the electrolysis of water, how does the calculated volume of water compare to the volume of water that actually decomposes? Explain possible discrepancies.

d. Draw a picture of the particles of water in the liquid and gaseous states at a temperature that you select. How far apart would the particles be? Justify the relative distances between particles in the two states by calculations. Assume that the density of liquid water is 1.0 g/mL, and that gaseous water acts as an ideal gas.

These questions are appropriate for students enrolled in an introductory chemistry course at the high school or college level. Having students both devise an experiment as suggested in A, and implement it, is an inquiry experience such as those advocated in the *Science Education Teaching Standards* (National Research Council, 1996). The inquiry could be made even more open by not giving clues such as density, and by asking students to supply any assumptions made.

The stoichiometry problem advocated in B is a volume-volume problem, that involves the density of water. It is an application problem that is not as routine as many given in chemistry texts.

C combines questions asked in A and B and is even more inquiry oriented. It becomes even more so if students are asked to state the assumptions, and if clues, such as density, are not given.

The particle question given in D requires students to use the density of a gas and the density of the liquid to determine volume ratios. They must then realize that the relative distance between particles will be the cube root of the volumes.

Questions such as those given above help students integrate the macroscopic, particulate, and symbolic representations of matter and thus increase their conceptual understanding. Individual conceptual networks are most likely being linked in long-term memory.

Evidence for the effectiveness of integrating the three levels of representing matter is provided by Russell et al. (1997). They reported an increase in conceptual understanding of chemical equilibrium when they integrated the three levels in an introductory chemistry course using computer-based materials.

Using ConcepTests

ConcepTests are multiple choice tests that are used in class to foster peer interaction among students. They were first used by Mazur during physics instruction at Harvard in the early 1990s and who has found them to increase student achievement (Mazur, 1997). They have been used in chemistry by Ellis (NISE website) and Kovac (1999). ConcepTests are not used for grading purposes, but to help students understand concepts more completely. Mazur uses them in the lecture with the following format: Instructor presents a ConcepTest question to the class, students formulate and record their individual answers, students share their answers and convince one another of the correct response, students record their revised answers (optional) and provide this feedback to the instructor, and the instructor gives the explanation of the correct answer. The process takes only about seven minutes and is repeated about three times during the lecture.

The author has modified the use of ConcepTests in an *Introduction to Scientific Inquiry* class that emphasizes chemistry for prospective elementary teachers. Students, who sit at tables of four in the lab/lecture sessions, are pre-assigned roles of facilitator, recorder, and spokesperson. They are given one to three multiple choice ConcepTest questions on a given concept. After each student answers the questions individually, the group recorder records each student's response, and the facilitator guides the peer interaction that occurs to reach consensus on each

ConcepTest: Changes in Matter

Which of the following are true statements?
A. The hard candy melted in my mouth.
B. When the sugar on the stove was heated too long it burned.
C. When bread was left too long in the toaster, it decomposed.

Figure 1. Concep Test on changes in matter.

question. The groups' answers are then recorded on a card or white-board which is displayed to the instructor and rest of the class. After noting whether there is class consensus, the instructor calls on the designated spokesperson at given tables to provide the explanation of the answers.

Although this process normally takes about 20 minutes, students remain on task the entire time. Having students give the explanation frequently takes longer than if the instructor had provided the explanation, but it also provides students an opportunity to formulate good answers to multiple choice questions. The assessment in the course corresponds to the class use of the multiple choice ConcepTests in that every test contains a number of multiple choice questions in which the students must write an explanation of why they selected a certain answer and why they rejected the other choices.

An example of a ConcepTest item that has been used for instruction in chemistry that has focused on the difference among decomposition, burning, melting, and dissolving is shown in Figure 1.

Discussion of the questions results in the following explanations:

a. False. Hard candy is usually made primarily of sugar. The melting point of sugar is higher than the temperature inside the mouth. The candy dissolves in the mouth.

b. False. Burning is the union of oxygen with a substance in which heat and light are produced. It is an exothermic reaction. When sugar is removed from the burner of the stove, the reaction stops. The sugar does not glow or produce heat. The black carbon that is formed is evidence that decomposition has occurred. If the carbon burned, it would produce carbon dioxide, a colorless gas so the sugar primarily decomposes although other reactions also occur.

c. True. Some students will think that this is burning like the sugar reaction described above. Others think that decomposition produces a bad odor, and because this doesn't occur, think that this could not be a decomposition reaction.

Multiple choice tests given during the semester provide an excellent resource for ConcepTest foils. When students are asked to explain their selection of the correct answer on multiple choice exams, common misconceptions are made known. Hence these plausible explanations can be incorporated into ConcepTests so that they become addressed during class discussions in future semesters.

The use of ConcepTests in instruction utilizes peer instruction which is a major component of the social constructivist philosophy. By using appropriate questions, students' cognitive conflict occurs which is resolved through peer interaction. As a result, students build a more appropriate network of concepts in their long-term memory.

Laboratory Investigations Using the Learning Cycle

Most laboratory activities and investigations in chemistry can make use of the social constructivist model of learning. An example of a physical science program that uses this approach is *Powerful Ideas in Physical Science* (1996), a college textbook for non-science majors. Many of the investigations in this book are related to everyday phenomena and begin with a question that frequently has an answer that is counter-intuitive. Students first answer the question individually, and then compare answers with their fellow students. They then work in collaborative groups answering the question with the evidence they collect, reach a group conclusion, and then reflect on how their initial answer has changed as a result of the investigation and discussion. The process is very similar to that used in ConcepTests.

An example of a very simple laboratory activity based on the Learning-Cycle might consist of the following condensed version of a student laboratory activity as shown in Figure 2.

During the Invention stage, that occurs between the Exploration and the Application stages, students are asked to group materials that act in similar ways. By asking appropriate questions, the teacher establishes the differences among melting, decomposing, and burning.

Some appropriate questions include:

- How can you tell when something melts, decomposes, or burns?

- Which usually occurs first? Melting, decomposing, or burning? Why?
- What is the appearance of something that melts, decomposes or burns?
- What conditions are necessary for something to melt, decompose, or burn?
- On the particulate level, what happens when something melts, decomposes, or burns?
- Write equations that represent any changes that occur in heating the materials involved in the Exploration.
- Why did nothing happen to some of the materials that were heated?

Laboratory Investigations using Problem-Based-Learning

The laboratory activity described above represents an approach to inquiry that is quite structured and teacher directed. It usually includes a formal and direct teacher instruction during the Invention stage. In Problem-Based-Learning which is based on Situated Cognition, students exercise more initiative when they devise a real-world problem that they would like to solve, or are at least involved in devising and carrying out their own plan to solve a problem supplied by their instructor. More directed problems, and the solutions devised by groups of students working collaboratively on different aspects of the problem, may be more discipline specific than the interdisciplinary ones devised by students. Hence this approach may be more suitable for chemistry instruction. As noted by Domin (1999), problem-based laboratory instruction is not new. It was reported by Young in 1950s.

An example of a problem that may be suitable for middle school or high school chemistry students that could be related to burning, melting, and decomposition might be related to making candles. It could be stated as a problem with some ambiguity as to the meaning of the word "best" as follows:

Candle-Making Problem: You decide to go into the candle-making business. What materials make the best candles? Support your findings by testing and making candles.

Students in the class are divided into groups of four. As a group they must first decide on how they will define the word "best." Considerations might include cost, stability of flame, brightness of flame, cleanliness of the flame, availability of materials, size, physical appearance, odor, etc.

Questions generated by the problem solving activity could include the following:

- What is the function of the wick?
- What is the function of the solid?
- What kinds of materials make the best wick?
- What kinds of materials make the best fuel?
- Why do some solids produce black smoke?
- What is the white material that is emitted from the wick when the candle is blown out?

Activity: Melting, Burning, Decomposing?

Question:
What happens when a substance is heated? Does it melt, decompose or burn? What is the difference between melting, decomposing, and burning?

What do you think?
(space provided for answer)

What does your group think?
(space provided for answer)

Exploration
Place small quantities (about the size of a pea) of the substances listed on a tin can lid that is placed on an iron ring attached to a ring stand. Heat each one gently for about two minutes. Note carefully in a table any changes that occur as you heat them. Substances include: sugar, salt, sulfur, iron, water, charcoal, etc. Which changes include melting, decomposing, or burning?

Invention *(See below for teacher led intervention.)*

Application
Place some wood splints in the test tube apparatus supplied by your teacher. Follow the directions given by your teacher. Heat the wood splints until they become black. Collect and test the wood, the liquids and gases to determine whether they burn. Describe the products in each step in the process, and try to identify if and when melting, burning, or decomposing is occurring.

Further Thought
What does your group think now? What is the difference between melting, decomposing, and burning?
(space provided for answer)

Do you think that changes in mass would result when substances melt, decompose, or burn? Devise a method to test your thinking?
(space provided for answer)

Figure 2. Laboratory activity using the Learning Cycle.

- What are the properties of the solids and the wicks?
- What is the difference between melting the solid and burning the solid?
- How can you represent symbolically the melting and burning of the solid?
- What is happening on the particle level in burning and melting?
- What effect does changing the diameter of the wick have on burning?
- What effect does changing the diameter of the solid have on burning?
- How can I modify the candle to make it re-ignite on its own if the wind blows it out?
- Does the candle lose mass when it burns?
- If I burn a candle under a jar, will the candle go out?
- Is the length of time that a candle burns under a jar dependent on the volume of the jar?
- Is anything produced when a candle burns? If so, what is it? How could I tell? Is it dangerous to inhale?
- How could be made to burn longer?
- If water is produced when a candle burns, how can water be used to out fires? Why doesn't it put out itself?

A variation of Problem-Based-Learning used by the author in her *Introduction to Scientific Inquiry* course gives students an opportunity to test a hypothesis. Students are asked: (1) *What are the factors that increase the rate of dissolving a solid in a liquid?* and (2) *Select one factor and test the hypothesis that the factor selected increases the rate.*

Prior to this exercise, students have done laboratory activities that included practice in gaining the skills necessary for hypothesis testing such as making observations and inferences, controlling variables, making graphs, etc. Students follow the same format as suggested earlier which includes individual thought, *What do you think?*; group collaboration, *What does your group think?*; performing the activity; and reflection on what students have learned, *What does your group think now?* They have also worked collaboratively using ConcepTests and the Learning Cycle.

After the *group thinking session*, the instructor solicits and displays the factors that might affect the rate of dissolving. Each student group selects one of the factors and then writes a plan on how they will test the hypothesis. Because of the cost involved in supplying materials, students are restricted to the solutes of salt, sugar, and hard candies, and the use of water as the solvent. Each group tests at least two of the materials to determine if they behave in a similar manner. The instructor acts as a consultant and answers questions about their procedures. Students determine the quantities of materials they will use, and how they will define the dependent, independent and controlled variables. They are supplied with magnifying glasses and microscopes (to compare particle size), hot plates and thermometers, various kinds of table salt, sucrose, and hard candies (powered, table, crystalline), graduated cylinders, funnels, beakers, balances, mortars and pestles, etc. Students have two hours to complete the data collection. They make their graphs and prepare their written and oral reports outside of class. At the next class session students make five minute presentations of their results.

In addition to acquiring skills related to the science processes, students learn the meaning of dissolving, the meaning of rate, the difference between time and rate, the fact that salt and sugar are not equally soluble, how surface area, temperature and quantities of solute and solvent affect dissolving rate, and the appropriateness of making smooth line graphs versus bar or broken line graphs. Students rate this lab as one of best experiences in the course even though it requires more thought on their part, and also more work outside of class.

Conclusions

There are many different teaching strategies that are based on the Information Processing Model and the Social Constructivist Theory of learning. Four that work for the author have been described, however, no statistical findings support their use in the author's teaching. These range from the integration of the three ways of representing matter and the use of ConcepTests that can be done in a conventional lecture to use of the Learning Cycle and Problem-Based-Learning in laboratory instruction. It is highly recommended that the reader visit the NISE website to examine additional tchniques/strategies that are being implemented by other science instructors in introductory courses. These include: Attitude Inventory, ConcepTests, Concept Mapping, Conceptual Diagnostic Test, Interviews, Integrated Lab Reports, Performance Assessment, Portfolios, Scoring Rubrics, and Weekly Reports.

As with any educational innovation, teaching strategies must be adapted to the physical conditions of the learning situation, the type of learners and course, and the personality of the instructor. In addition, care must be taken to provide sufficient variety in instruction, not only to provide for the diversity of the types of students in a given class, but because sometimes the combination of strategies has beneficial results. For example, educational research frequently shows that combining abstract instruction with more concrete instruction can be powerful, and may lead to higher levels of transferability (Anderson, Reder, and Simon, 1996). In the United States, two NSF supported projects that are combining the use of many strategies, and therefore make analyzing the effectiveness of particular strategies very difficult. These are the New Traditions Program (Landis et al., 1998) which makes use of ConcepTests and the ChemLinks Program (Anthony et al., 1998) which links instruction to everyday phenomena. Each of these shows great promise in substantially changing how chemistry is taught in introductory courses.

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