Improving Teaching and Learning through Chemistry Education Research: A Look to the Future*

Dorothy Gabel**
School of Education, Indiana University, Bloomington, IN 47408

The complexity of chemistry has implications for the teaching of chemistry today. That chemistry is a very complex subject is shown from the research on problem solving and misconceptions that has dominated the field during the past 15 years. For almost any topic that is taught in introductory chemistry courses, research on the identification of misconceptions has been conducted. Reviews of chemistry misconceptions include those by Andersson (*1*), Gabel and Bunce (*2*), Griffiths (*3*), Krajcik (*4*), Nakleh (*5*), Stavy (*6*), and Wandersee, Mintzes, and Novak (*7*).

A study by Bodner (*8*) based on the work of Osborne and Cosgrove (*9*) adds insight on how widespread misconceptions are. Bodner asked incoming graduate students with undergraduate majors in chemistry the following question: "Assume that a beaker of water on a hot plate has been boiling for an hour. Within the liquid, bubbles can be seen rising to the surface. What are the bubbles made of?" (p 385). Bodner found that 70% of the students answered water vapor, steam, or molecules of water. However almost 20% suggested that the bubbles contained air or oxygen, and 5% that it was a mixture of hydrogen and oxygen gases. Many of these students had misconceptions similar to those of elementary school children as reported by Osborne and Cosgrove.

Students possess these misconceptions and solve problems using algorithms because of the complex nature of chemistry concepts and because of the way the concepts are taught. In this paper, the complexity of chemistry concepts and the identification of instructional barriers are discussed in terms of current learning theories, and recommendations for teaching to improve students' conceptual understanding are made.

Barriers to Learning Chemistry

Many of the concepts studied in chemistry are abstract, and are inexplicable without the use of analogies or models. Consider some of the first concepts presented in many science texts for children in elementary school. These include such concepts as element and compound, and chemical and physical change. The distinction between an element and a compound generally taught to children at the phenomenon or macroscopic level is that elements cannot be decomposed by ordinary chemical means, whereas compounds can be. However, the activity used to make the distinction is abstruse. If common materials such as salt, water, sugar, and sulfur are heated with a burner flame to demonstrate the differences, nothing happens to the salt, the water boils away (said by children to disappear), the sugar decomposes (said by children to burn), and the sulfur melts and then burns. The distinction between elements and compounds cannot be easily made from this activity without resorting to explanations using molecular models representing compounds and elements.

A similar situation exists with the distinction between physical and chemical change. When fourth, fifth, and sixth grade children in a Saturday Science program at Indiana University were asked to describe the difference, many children included the concept of reversibility in their answer. Students said that physical changes were reversible and chemical changes were irreversible. The appropriate response, that chemical changes result in the formation of new substances with different characteristic properties, was never mentioned.

Misconceptions such as the above might be linked to the high density of chemistry concepts in elementary science textbooks (*10*). This makes learning them difficult, and results in too few examples being given from which children might make inferences. For example, in one elementary textbook series, the following statements are included in the introduction to chemical change, perhaps leading to the idea of irreversibility (*11*, p 182):

> Often there are basic changes in matter. For example, a cake is made from sugar, flour, and other materials. You can tell the physical properties of these materials. But once the cake is made, there is no way to change it back to the materials of which it is made. The same is true of an egg. Once it is cooked, there is no way to change it back.
>
> When matter changes in this way , it changes chemically. Its properties change, and a new kind of matter is formed.

From statements such as the above, children may conclude that all chemical changes are irreversible because only two examples were given, and both were irreversible. This may even be reinforced by their limited prior knowledge about the reversibility of physical changes such as changes of state. As in the case of distinguishing between elements and compounds, it would appear to be more appropriate to explain the differences between chemical and physical change using molecular models.

Complex Nature of Chemistry: Threefold Representation of Matter

The above description of children's initial instruction in chemistry points to the complexity of the nature of chemistry. Matter, which is observed and can be studied on the macroscopic level, can also be described on the microscopic level, and sometimes in so doing, the explanation appears to be more definitive. To complicate matters more, chemists can represent both the macroscopic and the microscopic levels symbolically through the use of chemical symbols, chemical formulas, and chemical equations. As Johnstone (*12*) has indicated, the nature of scientific concepts and the threefold

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**Email: *gabel@indiana. edu.*

manner of representing science, as shown in Figure 1, make science difficult to learn. Johnstone states that understanding science on three levels is not unique to chemistry, and thus uses terms that are more generalizable to counterparts in biology and physics. An additional factor to add to the complexity of chemistry is the frequent use of mathematical symbols, formulas, and equations to express relationships at the macroscopic and microscopic levels.

The primary barrier to understanding chemistry, however, is not the existence of the three levels of representing matter. It is that chemistry instruction occurs predominantly on the most abstract level, the symbolic level. A cursory examination of almost any introductory chemistry textbook supports this assertion. While it is true, as indicated by Johnstone (*12*), that it is not necessary to always link the three levels in teaching, it is important that teachers understand the threefold relationship so that it can be conveyed to their students. It is my experience after making presentations to high school teachers about integrating the three levels, that many teachers have not considered it in their own thinking. This lack of understanding is evident from the data obtained in an international study by Dori, Gabel, Bunce, Barnea, and Hameiri (*13*), where teachers were shown a picture of water molecules separated from one another as they are depicted in most textbooks and asked whether the picture represented water as a solid, liquid, or gas or a combination of these. Data analysis showed that there was little agreement among the teachers on what phase the picture represented.

An important research question about using the threefold representation of matter in instruction relates to the use of analogies and models in learning. In order to understand the microscopic level, a person must be capable of associating particles with models or analogies. Likewise, the model must be associated with symbols. An unresolved question is the age level at which molecular models are understood by children, and the type of instruction that might make them meaningful. Even college students have difficulty relating analogies and models to chemical phenomena. In a study by Friedel, Gabel, and Samuel (*14*), fruit of definite mass and volume was used in problem solving as an analogy for chemical species reacting in definite proportions. The researchers found that many students were unable to match analogous fruit and chemical species problems that were solved in identical ways. Current research in this area in chemistry by Treagust, Duit, Joslin, and Lindauer (*15*), and in physics by Brown (*16*) and Grayson (*17*), who are studying the use of bridging analogies and concept substitution, respectively, may lead to better instruction. ("Bridging analogies" refers to using a series of closely related analogies that bring the learner successively closer to an acceptable concept.)

This ternary way of representing matter is particularly confusing to students (*18*). Even the symbols that chemists use can be interpreted in several ways. For example, does the symbol "Fe" stand for one atom of iron or for a sheet of iron. Because the three levels can be interpreted in more than one way, and because teachers unwittingly move from one level to another in lecturing, students fail to integrate the levels, which leads to a fragmented view of chemistry with many puzzling parts that do not seem to fit together. Helping students relate the three levels of representing matter has potential for improving conceptual understanding. An opportunity for doing this is through work in the laboratory.

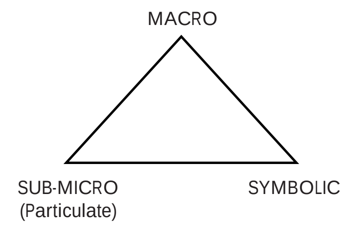

Figure 1. Three levels of chemistry. (NOTE: "Why Is Science Difficult to Learn? Things Are Seldom What They Seem", by A. H. Johnstone, *Journal of Computer Assisted Learning*, **1991,** *7*, 75. Copyright 1991 by Blackwell Science Ltd. Adapted with permission.)

Practical Work (Laboratory Activities)

A common component of chemistry instruction is the inclusion of practical or laboratory work. As indicated by Johnstone (*12*), one reason why students find chemistry difficult is that in the laboratory, they make observations at the macroscopic level, but instructors expect them to interpret their findings at the microscopic level. For example, a common laboratory activity at the secondary level that students do not understand well is the electrolysis of water. This is actually a complex activity that can be understood on the three levels mentioned earlier. Students view and measure the volume of the gases being produced, they could be asked to represent the decomposition of the water molecules using models of atoms and molecules, and they usually are asked to write a balanced formula equation using symbols for the reaction that has occurred. Even though most students can write the balanced formula equation after they have completed the electrolysis, they do not link the volume ratio of hydrogen to oxygen to 2:1 because it is logical to many students that molecules of greater mass (oxygen) should occupy more space than those of lesser mass (hydrogen). Avogadro's hypothesis is *not* self-evident! Many students complete the activity thinking that the whole test tube of water that the hydrogen has replaced has been decomposed. Evidence for this is found from the preliminary data on the trial version of an item on the ACS Conceptual Examination (*19*). A question asks students how much water has decomposed to produce a test tube containing 50.0 mL of hydrogen. Only 3% of students gave the correct response of 0.1 mL, whereas 50% of students thought that 50 mL of water decomposed.

Some of these "misconceptions" might have been eliminated by asking students to integrate the three ways of representing matter in the electrolysis activity. Students could be asked to draw particle pictures of equal samples of the hydrogen and oxygen in the two test tubes and relate this to the volumes of gases. They could be asked to calculate the volume of water that would decompose to produce the volume of gases that they had collected, and then to compare their calculated volume of water to the difference in water volume of the system before and after the electrolysis. This would take additional lab or class time, but would provide a greater conceptual understanding of the activity.

A review of research on laboratory instruction (*20*) indicates that it is not an effective teaching strategy to enhance conceptual understanding. Yet in an informal survey in several high schools in the USA (*21*) in which 64 chemistry students were asked about what they liked best about high school chemistry, 45 or 70% said that it was the laboratory activities. Perhaps if laboratory experiments were linked more effectively to the "lecture" or replaced the lecture, student learning would be enhanced. More research is needed such as that by Johnstone and Letton (*22*) on how to make the laboratory experience a more effective one. For example, we need to research the effectiveness of using Vee diagrams (*23*) in place of traditional laboratory reports. (Students using Vee diagrams write a condensed lab report on the right side of the V and link the their findings to concepts, principles, and theories previously learned on the left side of the V.) The lack of learning from laboratory experiences is not dependent on the complexity of the discipline of chemistry, but is one that we have created ourselves by failing to realize how little students are learning from laboratory experiences the way they are commonly structured.

Unfamiliar Materials

The use of unfamiliar materials in chemistry instruction appears to be an additional barrier to conceptual understanding, one that is unwittingly overlooked by textbook authors and chemistry teachers. When students do not recognize the name of a chemical with which they are dealing, they are not learning on the macroscopic level. The strings of letters comprising the names of unfamiliar chemicals are merely noninterpretable symbols. This makes learning more abstract.

Students live in a macroscopic world of matter, things that have mass and occupy space. Unfortunately, however, students do not perceive chemistry as related to their surroundings. They frequently think of chemicals as dangerous materials with strange-sounding chemical names (*24*). Problems at the ends of chapters are seldom about sugar, salt, wax, or lipstick. The chemical names that are used are frequently not familiar to students so there is no way they can even imagine the physical properties of the material being considered. This is made very evident in some commercials on U.S. television where ice cream producers have children read the names of the ingredients. In Brand A (sponsored by the commercial) the listed ingredients are cream, sugar, and fruit, whereas Brand B consists of chemicals that the children stumble over in reading the ingredient list.

A study by Phelps (*25*) indicates that using materials familiar to college students has beneficial effects for both majors and nonmajors. Not only is the learning on the more familiar macroscopic level, but students appear to be more motivated to learn about things related to their everyday life.

Use of Language

Another barrier to understanding chemistry that is not related to the threefold representation of matter given by Johnstone (*12*) is the use of language (*26*). In English, we are very familiar with expressions in which words in common usage have a different meaning from their meaning when applied to chemistry. For example, we say, "the coffee is strong," rather than "the coffee is concentrated," or "the candy melts in your mouth," rather than "the candy dissolves in your mouth." In the USA the word "substance" is frequently used as a synonym for matter and it is necessary to say "pure substance" to reduce the ambiguity. In the international study by Dori et al. (*13*), teachers were asked to select the material that was a substance from a group of five materials. These included concrete, sugar, Pepsi, milk, and all of the above. In the U.S. sample only 48% gave a correct answer (sugar). About 40% indicated that all of the materials were substances. In Israel, when the test was translated into Hebrew there was no equivalent word for substance so substance was translated as "pure matter", and about 83% got the item correct. Other languages also have words whose scientific meaning differs from their meaning in everyday usage. Again, this problem is not necessarily related to the complexity of chemistry per se, and can be solved by carefully defining terms and by selecting appropriate vocabulary.

Structure of the Discipline

In addition to the complex nature of chemistry, the structure of chemistry itself may be an instructional barrier. Several questions must be asked. Does chemistry have one set structure, and if so, what is it? A logical structure of chemistry based on composition and structure, energy, and time, has been proposed by Jensen (*27*). Is this structure of the discipline an appropriate structure for instruction? Examination of textbooks shows that a variety of instructional structures exist. A common one is to present more theoretical concepts of atomic theory and bonding that are best explained on the microscopic level first, before presenting descriptive chemistry at the macroscopic level. To those who already understand a great amount of chemistry (textbook authors) this structure appears to make sense. There are, however, unanswered questions. How important is this structure in teaching chemistry to neophytes? Does atomic structure need to be taught at the beginning of the chemistry course, as it commonly is, to make learning more effective? Some concepts are needed throughout the entire study of chemistry, such as moles, molecules, substances, and solutions. The careful work in the area of the conceptual structure of the chemistry curriculum by de Vos, van Berkel, and Verdonk (*28*) provides a framework for teaching chemistry based on continuity of conceptual understanding. Yet as they point out, this is frequently not followed because of current societal demands on the curriculum. Are structures such as those incorporated in ChemCom (*29*), Chemistry in Context (*30*), ChemLinks and the ModularCHEM Consortia materials (*31*), and in New Traditions modules (*32*), in which chemistry is introduced in relevant contexts, equally or more effective? An examination of how persons learn provides answers to these questions and others about the barriers to learning chemistry.

Conceptual Understanding of Chemistry and the Information Processing Model

The way students learn chemistry can be explained using an information processing model recently featured in *Newsweek* (*33*) and represented schematically by Johnstone (*34*) as shown in Figure 2. New information from the senses enters the working or short-term memory, which has a limited capacity. This information either is lost or passes into the long-term memory. Whether the fact or concept is retained depends on its complexity and the space available in short-term memory. For example, it is easier to remember short number sequences than long sequences. Taking notes and repeating telephone numbers appears "to extend" short-term memory. The information that passes into long-term memory interacts with information already stored there as part of an expanding network of concepts; it may serve as a linkage between smaller networks to produce larger networks or it may remain in isolation.

Many chemistry concepts are very abstract. If there is nothing in long-term memory to which a new concept can be related, then it will either not be stored, or it will be stored as a single entity. Hence, if something does exist to which the new concept can be related, then learning occurs. It is thought that analogies can take on this function, but in order to be effective, the students must understand the analogy and see the link between the concept being taught and the preexisting, familiar concept in long-term memory. These thought patterns existing in long-term memory can be represented by concept maps. Novices in a given subject area have very simple maps containing concepts that may contain "misconceptions" from a scientific point of view. Experts in the field have very complex and well-connected maps. When one part of the map is triggered by an outside stimulus, the expert is privy to an enormous number of related concepts. Some of the evidence for this relates to the way experts solve problems. They think for a period of time and then retrieve much information. A novice, on the other hand, brings out disconnected pieces of information. Learning science consists of making intricate networks in long-term memory more consistent with accepted scientific thought.

The information processing model of learning helps to explain the barriers to learning chemistry that were identified earlier: the complex nature of chemistry concepts, the threefold representation of matter, practical work, unfamiliar materials, language, and the structure of the discipline.

First consider barriers to learning associated with long-term memory. These include using unfamiliar materials and using language that has both a common and a scientific meaning. Although it is possible for isolated information to be added to long-term memory, more effective learning occurs when new information is linked to information that is already stored there. Existing networks are then expanded, and a person can have the exhilaration of seeing how concepts fit together to make sense of the world. Novice chemists, whether at the elementary or college level, are familiar with matter as the ordinary objects that surround them. Taking this into consideration, chemistry instruction should be based on the familiar macroscopic world. For example, using phenomena such as melting ice cream and margarine and comparing these to the melting of ice will be a more meaningful initial experience than melting mothballs. Using multiplication and division to solve simple problems might be more conceptually meaningful than creating a new system of calculation known as the "factor-label method".

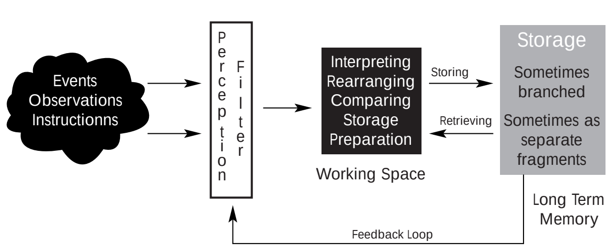

Figure 2. Information processing model (after Johnstone, A. H. *J. Chem. Educ.* **1997,** *74*, 262–268).

Students have also developed a vernacular vocabulary of words that have a dual meaning and for which only the common meaning is stored in long-term memory. Hence, for students to be successful in chemistry, the meaning of words such as substance, melt, dissolve, and burn will need to be defined from the scientific viewpoint. Otherwise when these words are used in instruction, the student will be thinking one thing, the instructor another.

The building of concept networks in long-term memory also has significance in considering the structure of chemistry as a discipline. Experienced chemists think in terms of atoms and molecules, and introductory courses are frequently structured to build the world from the particulate level to the macroscopic level. Ideally atoms and molecules provide explanations for the way matter behaves. It would appear to be more consistent with the way people learn for students to study the familiar macroscopic world first, and then explain that world using the particulate nature of matter. In this way new concepts are anchored on the concepts of a preexisting network in long-term memory. Perhaps this approach would help eliminate some chemistry misconceptions.

In terms of short-term memory, the limited space available suggests that the three ways of representing matter not be introduced simultaneously to novice learners. However, once they are introduced, students should be given numerous opportunities to relate the three representations so that multiple linkages are formed in long-term memory. Chemistry appears to be very complex to the novice learner because there are many concepts that can be *observed* at the macroscopic level, but can only be *explained* at the particulate level. In the minds of many students, there is no connection between the macroscopic, particulate, and symbolic levels. This may have been what happened with the graduate students tested by Bodner (*8*). They knew chemistry in each mode, but there were no linkages.

The limited space in short-term memory also explains why the use of unfamiliar chemicals, and our current mode of laboratory work, makes learning difficult. If a word or a chemical species is unfamiliar, it will take up a much larger space in short-term memory than something familiar because an inordinate amount of time must be taken to make sense of it. The same is true with laboratory work. As Johnstone (*12*) indicated, if an experiment contains what he terms "noise" (e.g., unessential information such as directions on how to set up elaborate instrumentation), students must try to make sense of this, and this occupies space in short-term memory.

Constructing Knowledge in a Social Context

The way students process new information is affected by the setting in which they learn. Today's students learn in a variety of situations. They acquire knowledge by using computers, reading books, listening to lectures, doing laboratory activities, and participating in discussions. Use of the information processing model to restructure instruction, although necessary, is insufficient to stimulate student learning.

The following example is given as an illustration of how many students learn in today's classrooms.

Chris was a gifted and talented student who had been enrolled in a special school in the USA since grade 6. After four years in the program, he took a special chemistry course for gifted students in grade 10. As part of an action research project (*35*), a high school chemistry teacher who was learning interview techniques interviewed Chris during the summer following his special chemistry course. The teacher had a Ziploc bag containing a small pile of baking soda and an open vial of vinegar. He flattened the bag with his hand to remove the air, sealed the bag, and tipped over the vial so the vinegar mixed with the baking soda. Simultaneously the interviewer was explaining to Chris what he was doing.

Chris had undoubtedly seen this demonstration before. It is a very common one, performed at almost every grade level in every school in the USA. The interviewer asked Chris this question. What gas is being produced in the bag? Chris said, “Carbon.” The interviewer was rather taken aback and asked the question a second time thinking that perhaps he had not hear the entire response. This time Chris’s response was “Carbon, my teacher always told me that carbon is produced in cases like this.”

The reason why Chris had no idea that carbon dioxide, not carbon, was the gaseous product of the reaction between baking soda and vinegar may be understood using the information processing model described earlier. Perhaps Chris had not made the linkage between the macroscopic level (carbon’s color compared with that of carbon dioxide) and the symbolic level in the balanced equation, and these levels were isolated information in long-term memory. However, another possible reason that he failed to think about the situation and depended on his memory for the answer was that chemistry was presented to him as something to be memorized rather than to be understood.

As indicated by Osborne (*36*), social constructivism has enabled the development of some innovative teaching strategies that would assist Chris and other students in the learning of chemistry. Although few scientists accept the tenets of radical constructivism that knowledge does not represent reality (*37*) and that knowledge is socially negotiated (*38*), most accept the social constructivist view described by Driver and Oldham (*39*). The sketch by Krajcik (*4*) shown in Figure 3 provides a commonly held current view on how students learn. According to this position, students construct new

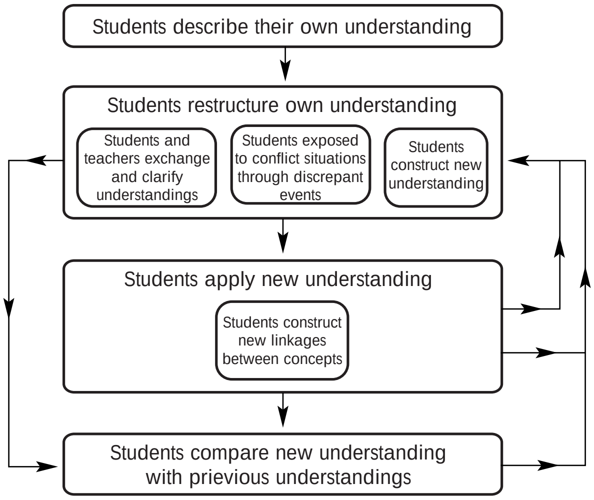

Figure 3. Social constructivist model (NOTE: From “Developing Students’ Understanding of Chemical Concepts”, by J. S. Krajcik, 1994, in *The Psychology of Learning Science*, p 130. Copyright 1994 by Lawrence Erlbaum Associates, Inc. Reprinted with permission.)

understanding only after they have considered their current understanding. This is facilitated through social interaction with their instructors, other students, or perhaps a computer. This interaction can be concerned with the introduction of conflict situations that help students create dissatisfaction with their current views, modification of current views (partial restructuring) using concept substitution or analogies (*16, 17, 40, 41*), or reflection on the meaning of text through self-explanation (*42, 43*). In the case of Chris, who substituted memorization for thinking, reflection and social interaction were probably not part of his learning experiences.

Both the information processing model and social constructivist theory must be considered when examining learning in the 21st century. One without the other will not produce conceptual learning. Without reflection on information in long-term memory, any misconceptions present remain unaddressed and additional information enters long-term memory in a memorized mode as a separate entity. With reflection, students examine misconceptions in light of new information, revise their existing understanding, and re-store it in a more integrated way that is in better accord with accepted scientific thinking. With reflection on what is already stored in long term memory, new information entering the memory is linked to information already present to form integrated networks that enhance problem solving.

Chemistry Education Research for the 21st Century

It is difficult to predict what learning will look like during this coming century, but there are some indicators of what can be expected. John Petersen, a U.S. futurist and author of *The Road to 2015*, predicted that the future will involve a revolution of scientific ideas (*44*). He indicates that the growth of scientific knowledge is proceeding at a revolutionary rather than an evolutionary rate, changing at an exponential rate rather than linearly. New technology is also expanding rapidly. Although it took 20 years for telephones to be owned by a million people, it has only taken three years for personal computers to reach this level of ownership. Petersen believes that there will be a power shift away from force and money to information and knowledge as the commodities of the future. Educators already know the power of the World Wide Web and the avenues this opens up for learning. Today entire curriculum projects such as the National Science Teachers Association’s Scope, Sequence & Coordination Program (*45*) for secondary science can be downloaded from the Web and teachers can print out those units they wish to use in their classrooms. Petersen indicates that computers and telephone communications will replace boom boxes and will be as commonplace as paper was at the turn of the 20th century. In addition, there is every indication that classrooms are becoming more diversified, more international, and more heterogeneous in terms of students’ backgrounds, needs, and interests.

Unfortunately, chemistry education research in the 20th century has had little influence on the way chemistry is taught. The changes that have occurred in textbooks during the past four decades have not been driven to any great extent by research findings. Although chemistry education researchers have identified common misconceptions for almost every topic taught in introductory science courses, probably nine out of ten instructors are not aware of these misconceptions or do not utilize ways to counteract them in instruction.

Will this change in the 21st century? Perhaps as instructors more often administer conceptual exams such as the one recently published by the American Chemical Society Exams Institute (*19*), they will realize the need to change instructional practices. Because human beings have developed over a long period of time, the way students learn in the 21st century will not differ dramatically from the way they learn today. Time for reflection and cognitive conflict will still be important, and concepts will be learned more efficiently if they are structured in certain ways. However, the settings will change, and this will call for research by chemistry educators using the aforementioned models and theories, or perhaps new ones that explain learning better.

As information grows, there will be a need to learn basic concepts and also to become specialized. This will require an increased use of technology. With students immersed in virtual reality, the richness of the immersion may produce more efficient learning, creating another rich area for research. We have already seen the positive effects of using technology in teaching. For example, Williamson and Abraham (*46*) found that students understand the particulate nature of matter better when using computer simulations than when using still diagrams such as pictures and transparencies.

As the population becomes more heterogeneous and researchers learn more about how students of diverse backgrounds, learning styles, and ability acquire knowledge, the way chemistry content is structured will become increasingly important. Studies by van Hoeve-Brouwer (*47*) and others from the Centre for Science and Mathematics Education at Utrecht University and by Ben-Zvi and Hofstein (*48*) at the Weizmann Institute of Science in Israel serve as models of how chemistry education research should accompany curriculum development. The structuring of chemistry courses using computers may make current research on misconceptions more useful, as computer programs could incorporate ways for students to explore their misconceptions. More effort is needed within the curriculum itself to address students' misconceptions.

In conjunction with this, continued research is needed on how students become successful problem solvers. This may relate directly to the information processing model. Hence the work of Niaz (*49*) in Venezuela and those who will follow after him is very important.

As careers become more specialized, research on what chemistry is appropriate for students of different ages to enable them to select a scientific or nonscientific career becomes more important. The chemistry needed to become a good citizen or to lead a fruitful life must be determined. Chemistry appropriate for the artist, the foods specialist, the nurse, etc., will become increasingly important. Does the nonscience major need to understand the molecular and symbolic levels in chemistry? An interesting approach to this question has been undertaken in curriculum development in Scotland, where chemistry is taught on the macroscopic level and students have a choice of learning at the symbolic and particulate levels according to their interest (*12*). More relevant and humanistic approaches will be needed to offset or balance the more carefully structured technological approaches. In the USA, *ChemCom* (*29*) and *Chemistry in Context* (*30*), and in Australia, the contextual approach in the Victorian state syllabus as described by Beasley (*50*), are helping to fulfill this need now. Research on the effectiveness of these approaches for all types of students is needed.

All the aforementioned examples refer to chemistry content. Research is also needed on how diverse groups best learn chemistry in various educational settings. Opportunities for research in the 21st century abound, and some of the foundation is already in place. Chemistry education researchers need to think of the future and move forward in the areas that will be of greatest importance in the 21st century. Concurrently, there is a need to focus on ways to incorporate current research findings into the teaching and learning of chemistry today.

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