Prior Knowledge of Chemistry Students: Chemistry K–8

by Dorothy L. Gabel and Karen J. Stucky

Dorothy L. Gabel *is Professor Emerita of Science Education at Indiana University. She earned her Ph.D. at Purdue University under the guidance of J. Dudley Herron. Her* Saturday Science *program and work on the* Indiana Core 40 Assessment *have impacted thousands of teachers and elementary school children. She has been honored with the Robert Carleton Award for Leadership in Science Education from the National Science Teachers Association and the Award for Achievement in Research for the Teaching and Learning of Chemistry from the American Chemical Society. Contact e-mail: gabel@indiana.edu*

Karen J. Stucky *is a retired teacher of upper elementary science and math. After retiring from the classroom and being the elementary science coordinator for our local school system, Karen became actively involved in informal museum education and professional development in science for teachers. She serves as Education Director at the WonderLab Museum of Science, Health and Technology, Monroe County Community School Corporation, in Bloomington, IN. She designs field trips, laboratory lessons, and teacher workshops at the museum. After a second retirement later this year, she will remain a consultant for the museum and for Delta Education doing FOSS training for teachers. Contact e-mail: kstucky@indiana.edu*

Introduction

A guest editorial on the Editor's Page in the August 28, 2006, issue of *C&E News* entitled "Forget Chemistry" (Wolke, 2006) contained an important message about chemistry instruction for children. The author expressed the opinion that

> *"In our efforts to swell the ebbing stream of students choosing chemical careers, we may be trying too hard. We may put our faith in exposing children to chemistry at an early age in hopes that they will catch the "chemistry bug" before it (and they) are barely out of the larval stage. . . . But the usual children's enticements often turn out to be little more than magic shows that, frankly, generate little or no excitement about careers in chemistry. Let's face it: Neither colored liquids or fizzing baking soda are as fascinating to kids as the insides of a salamander or a black hole. A general captivation by Nature must be instilled before we can expect children to "specialize" in chemistry."*

Students' continued interest in majoring in chemistry at the college level is dependent on their success at the high school level and in their introductory college-level chemistry courses. Even if children "have been captivated by nature" at the elementary level, this is insufficient to encourage them to select chemistry as a career. For some students, success at the high school level is insufficient because of the way high school chemistry is taught or because at the elementary or middle school level, the content was beyond their comprehension.

For example, a young woman who recently graduated from a large state university and who earned the highest grade in the introductory chemistry course of about 500 students was selected as the secretary/assistant for a summer chemistry program for high school chemistry teachers. Asked why she waited to take the chemistry course until after she had graduated from the university with a major in psychology, she replied, "I didn't understand a thing in high school chemistry, even though I got an A in the course." She decided to major in psychology after examining a variety of textbooks in the university bookstore. She said that she found the content in the psychology books interesting and could understand the subject matter by reading! This young woman eventually wanted to become a veterinarian. After she graduated from college, only then did she feel confident that she would be able to pass the required chemistry and other science courses to fulfill her plans for the future.

Mike Ciesielski

The above account is not unusual. An excellent third-grade elementary teacher who is working part-time conducting science workshops for a publisher of one of the best science programs in the United States, was also turned-off to chemistry in college. She earned an "A" in an introductory chemistry course during her first semester. However, she dropped the second semester of chemistry because, as she said, "I didn't understand it." This teacher continues to teach third grade as her primary profession, even though she is lacking in background knowledge of basic chemistry concepts. Incidents such as these make one wonder about how many other prospective elementary science teachers and other excellent students are being turned-off to chemistry because of the way it is taught!

National Science Education Standards

Two different groups in the United States have produced standards for teaching children chemistry in kindergarten through grade twelve. These are part of the *National Science Education Standards* (NSES) and were developed by chemistry experts under the direction of the American Chemical Society and published by the National Academy Press (National Research Council, 1996) and the American Association for the Advancement of Science (1993), *Benchmarks for Science Literacy*.

The recommendations of the NSES and the *Benchmarks* are quite similar. One major difference is that the recommendations of the NSES are less specific about the appropriateness of specific ideas and content at particular grade levels. Recommendations in the NSES are made for grades K–4, 5–8, and 9–12, whereas recommendations in the *Benchmarks* are made for K–2, 3–5, 6–8, and 9–12. In terms of chemistry instruction, the NSES for elementary students do not include the study of atomic theory, whereas this is included in *Benchmarks*.

A study by Liu (2006) using a U.S. sample from the Third International Mathematics and Science Study found that

> *"…third-grade students were developing understanding on mixtures, and fourth-grade students were developing understanding on separating mixtures; seventh- and eighth-grade students were only at the beginning level of differentiating chemical properties from physical properties; they were not ready for the particulate model of chemical change."*

The findings suggest that the *Benchmarks* and the *Atlas of Science Literacy* (American Association for the Advancement of Science, 2001), a resource for curriculum development based on the standards, may have *overestimated* the competences of elementary middle school and high school students. The NSES may be more realistic in terms of chemistry instruction.

The study by Liu supports this, as does a study by Harrison and Treagust (2002).

Another problem is that both sets of standards are considered to be *minimal*. That is, many states include *additional* standards in their state standards for elementary and middle school students. This has, in turn, caused science textbook publishers to increase the content of their textbooks to meet the state standards by publishing specific textbooks for given states. In chemistry, for example, one textbook publisher includes introducing atoms in grade three for children in Indiana.

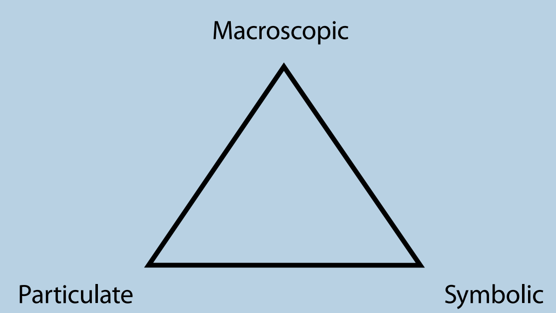
Even though both sets of standards mentioned above have recommendations concerning what children in the various grade levels should learn, the *No Child Left Behind* legislation has, in reality, often compelled schools to ignore science, while spending much more time on reading and math skills, which are tested by a wide variety of both state and national tests. In the June 4, 2007, issue of *Time Magazine*, a feature article entitled "Report Card on No Child Left Behind" stated that "because the law holds schools accountable only in reading and math, there is growing evidence that schools are giving short shrift to other subjects." This makes it even more important that teachers and schools carefully choose what concepts in science they will teach across the different grade levels in order to make the instruction more effective.

The Reform of Chemistry Education

In the 1960s, reform of science education focused on the science process skills of observing, inferring, classifying, predicting, communicating, controlling variables, measuring, and doing experiments. These skills are extremely important and need to continue to be emphasized. And now, students are expected to give explanations of their observations.

Chemistry educators have known for many years that chemistry can be taught on three different levels: macroscopic, particle, and symbolic (Johnstone, 1990, 1993) (see Fig. 1). Although the levels are displayed on an equilateral triangle, teachers should not infer that the three levels are equally easy to understand, nor should be taught to students of all grade levels. Studying chemistry at the macroscopic level is the easiest level to comprehend because this level is less abstract and more accessible, depending extensively on the use of the senses (in particular, seeing, and perhaps smelling, hearing, or touching (with caution), but never tasting).

Figure 1. Johnstone's levels of understanding chemistry.



Used with permission from the *Journal of Chemical Education*, Vol. 70, No. 9, 1993, pp 701 © 1993, Division of Chemical Education, Inc.

The other two levels of Johnstone's triangle (particulate and symbolic) are considerably more abstract and are not developmentally appropriate for most children in grades K–4 (and even in grades 5 and 6, and for some children in grades 7–9.) When topics such as atoms are introduced in grade 3 (as they are in one textbook series approved for adoption in some states), many children will memorize definitions. Even some teachers are challenged to explain the difference between an atom and a molecule. The complexity of understanding chemistry at the particulate level is simply inappropriate for elementary children.

There are numerous activities and experiments that can be done on the macroscopic level, which children in grades K–8 find interesting and exciting. Some are even mathematics related. An excellent example of a reference for appropriate activities for grades 3–8 is *Inquiry in Action: Investigating Matter Through Inquiry* (ACS). Unfortunately, what has happened in the past several years is that much of the content that used to be taught in high school chemistry courses in the 1950s has been moved to middle school or lower, even though it is not included in the NSES or *Benchmarks* for middle school children. If all children in the United States mastered either set of these standards, they would be ready for high school science courses where more complex content is appropriate.

Research on Children's Understanding of Chemistry

What does the research tell us about students' understanding of chemistry? We examine children's understanding of chemistry at the high school, middle school, and elementary school levels. We have included selected findings about high school students because it seems reasonable to conclude that if students at the high school level do not understand certain concepts that are also being introduced in middle or elementary schools, then these same concepts will not be understood by younger children either. Although we have examined a large number of studies (42) on this topic, we limit this review to those studies that seemed to be most relevant, very informative, comprehensive, and well researched. Studies that were examined were not limited to students in the United States because it was assumed that children's developmental levels are generally consistent across countries.

Many studies over the past 50 years have focused on children's understanding of chemistry on the particle and symbolic levels. This review will include cross-age studies, as well as studies of high school students that provide information about student understanding of the particle nature of matter and symbolic representations. If high school students have difficulty learning these aspects of chemistry, it is reasonable to assume that this content is probably too complex for most middle and elementary school students.

High School Students' Understanding of Chemistry. Griffiths and Preston (1992) interviewed 30 grade 12 students drawn from 10 high schools in Newfoundland on concepts relating to molecules and atoms. Students were classified into three groups: academic science (with at least two high school science courses and an average of above 75% university-bound science students), academic nonscience (no science courses and overall average of at least 75%), and nonacademic (average less than 75% and not taking science courses).

Table 1. Misconceptions of Grade 12 Students About Atoms and Molecules

Student Idea	% Students
1. Water molecules are composed of two or more solid spheres	70
2. A water molecule is macro in size.	50
3. Water molecules within a phase may have different sizes.	40
4. Water molecules in ice touch each other continuously leaving no space.	50
5. Collisions may result in a change of atomic size.	50
6. All atoms are alive.	50
7. Atoms are alive because they move.	50

Results of the study showed that there were 52 different misconceptions relating to atoms and molecules. Even the very best group had a considerable number of misconceptions. One-third or more of the sample shared 19 misconceptions. Some of the common misconceptions are listed in Table 1. If high school students of the top group in Newfoundland have these misconceptions, it follows that the misconceptions about atoms and molecules of the middle school students will be even more numerous. It is also likely that this same problem exists in the United States and other countries.

Another study that has implications for what chemistry concepts are appropriate for students of various grade levels was conducted by Abraham et al. (1994). They explored students' understanding of chemistry at grades 9, 11, and 12, and in an introductory college chemistry course and found that

- "Both reasoning ability and experience with concepts account for the understanding of chemistry concepts.
- Students at all levels tended not to use atomic and molecular explanations for chemical phenomena. Although the use of atomic and molecular models increases with increased exposure to chemistry concepts, it is still low, even among college students.
- There were no predictable patterns in the frequency of alternative conceptions with respect to experience with the concept…"

Middle School Students' Understanding of Chemistry. A recent comprehensive study of middle school students' understanding of chemistry by Nakhleh et al. (2005) compared middle school students' ideas about matter with those of elementary students. They found that most of the middle school students interviewed knew that matter was composed of atoms and molecules. Some students were able to use this information to explain processes such as phase changes of water but that their knowledge frameworks were inconsistent because of their fragmented ideas. This points to the difficulty of assimilating the particle level acquired by instruction into their formerly acquired macroscopic knowledge.

Elementary School Students' Understanding of Chemistry. An earlier comprehensive study by Nakhleh and Samarapungavan (1999) explored elementary school children's beliefs about the particulate nature of matter before they had any formal instruction on this topic. Fifteen students (ages 7–10) were interviewed concerning their understanding of the microscopic and macroscopic properties of solids, liquids, and gases, as well as their understanding of phase changes and dissolving. Sixty percent had macroparticulate beliefs; 20% had microparticulate beliefs, and 20% held macro-continuous beliefs about matter. The children's beliefs were not consistent across the variety of substances from continuous to particulate substances. An example of children's thinking is illustrated because Linda (age 8) "held a macroparticulate view of matter by stating that the substance was 'made of little pieces' or could be divided by human action." An excerpt of Linda's interview (Nakhleh and Samarapungavan, 1999, p. 787) is shown in Figure 2. Linda was classified as "macroparticulate" because her incomplete view of matter did not include that all of the particles were identical in size and shape, nor were they made of identical atoms. No student (ages 7–10) in the study had a completely accurate view of the composition of sugar.

Cross-Age Studies on Understanding Chemistry. As indicated earlier, Liu (2006) studied the competence levels in understanding the "matter concept" at grades 3 and 4, 7 and 8, and grade 12. Findings included:

- Third-grade children were beginning to recognize mixtures and to separate them.
- In grades 7 and 8, students had mastered recognizing mixtures.
- High school students had developed an understanding of molecular models and were beginning to understand atomic structure.

Figure 2. Elementary school child's thinking about particulate nature of matter.

Researcher	Now take a look at this sugar cube and say, is this just one big piece of material or is it made up of little bits?
Linda	*It's a little piece of sugar.*
Researcher	Okay, Now think about the smaller little pieces of sugar that this cube is made of. Uh, are they the same or different?
Linda	*Different.*
Researcher	Okay, can you tell me in what way they're different?
Linda	*They're all probably shaped different… I don't know how little they are. [Linda constructs Play-Doh models which are very small round and oval objects]*
Researcher	What shapes would these little pieces be, you think **they'd be all different** shapes?
Linda	*Kinda circle and kinda oval.*
Researcher	Okay [pause] You think that there would be any other shapes, like squares and triangles, or things like that?
Linda	Yeah [long pause].
Researcher	You know, this tiny little piece of sugar, uh, What would they taste like?
Linda	*Sweet.*
Researcher	Sweet. What color would they be?
Linda	*White. White and [pause] I dunno. White.*

Mike Ciesielski

An additional research report of Liu and Lesniak (2006) provides more details about the study in general. Cross-age studies of the matter concept, particularly when the same authors conduct the studies are extremely useful in determining the appropriate level at which chemistry concepts should be taught.

Conclusions and Recommendations

In an unpublished study now being prepared for publication by D. Gabel, L. Cardellini, and L. Wozniewski, data were collected on college students' understanding of three sets of concept-pairs, prior to and after taking an introductory college chemistry course in both the United States and Italy. The pairs were chemical vs. physical change, burning vs. decomposition, and melting vs. dissolving. All of these topics are included in the chemistry textbooks examined at the middle school level. The test contained a macroscopic, a particulate, and a symbolic question on each of the six concepts. Results indicated that there was no significant improvement by college chemistry students after one year of college chemistry. The average pretest score was 7.5, and average posttest score was 9.0 out of a possible 18. This indicates that if students do not learn about these everyday concepts before they take a high school or college chemistry course, they may never learn them! The above topics are appropriate for instruction at the upper elementary and middle school levels. The macroscopic level would be suitable for all children. The age level for the introduction of the particle and symbolic levels is questionable and will depend on the developmental level of the child. Presenting these concepts before students are developmentally ready is likely to turn students off from chemistry, rather than making them fans.

Because of this great diversity in chemistry instruction at the elementary and the middle school levels, as can be seen from the variety of textbooks and programs in use, it is very difficult to know exactly what chemistry concepts students understand when they enter high school. Of even greater concern, is whether students have had a positive experience when studying chemistry so that they are looking forward to taking high school chemistry and perhaps will even consider majoring in chemistry in college. As indicated by R. L. Wolke,

> *" The funnel that leads to chemical careers can have a very wide top. To collect more chemists at the bottom, we must pour more young science fans, not just chemistry fans, into the top, through the funnel. As more and more children are turned on to a broad array of natural wonders, they will sort themselves out while passing through the educational funnel, and a fair proportion will inevitably wind up in the chemical sciences."*

Let's hope that he is right, and give this a try!

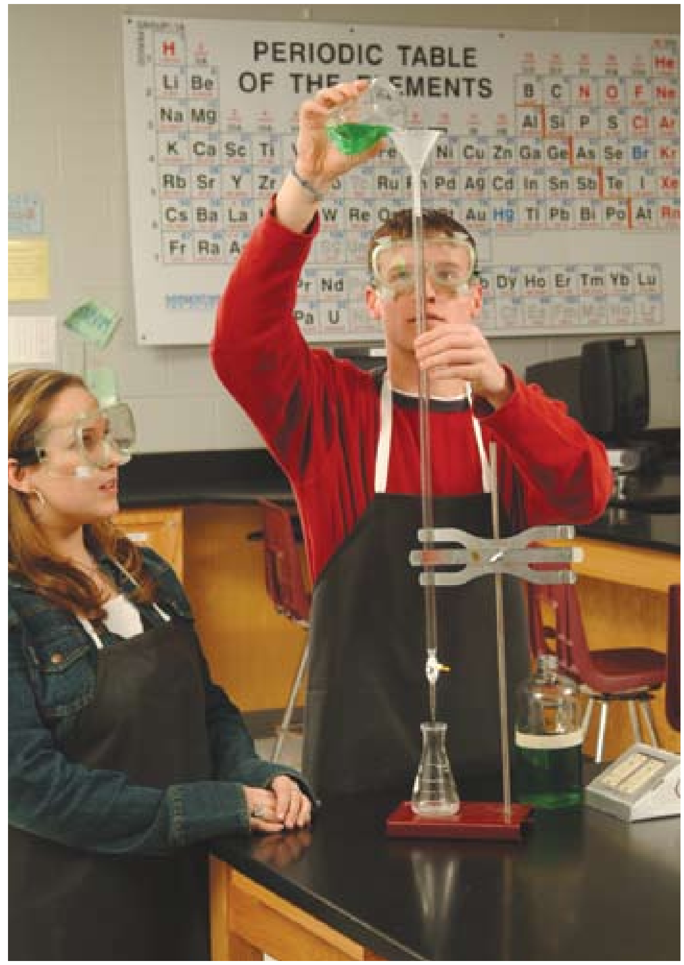
Recommended Readings

Keeley, P.; Eberle, F.; Farrin, L. *Uncovering Student Ideas in Science: 25 Formative Assessment Probes*, NSTA Press: Washington, DC, 2005. This book is very helpful in determining what high school students actually know.

Kessler, J.; Galvan, P. *Inquiry in Action: Investigating Matter Through Inquiry*, 2nd ed.; American Chemical Society: Washington, DC, 2005. This is an excellent reference for both activities for grades 3–8, as well as information about guided inquiry teaching techniques.

Linse, P. L.; Licht, P.; deVos, W.; Waarlo, A. J. *Relating Macroscopic Phenomena to Microscopic Particles*. CD-B Press: Utrecht, The Netherlands, Center for Science & Mathematics Education, University of Utrecht, 1990. This book contains the proceedings of a seminar held at the University of Utrecht. It contains seven plenary lectures and 19 invited papers, most of which are related to the teaching of chemistry at the macroscopic and microscopic levels. This book may be available from the Center for Science and Mathematics Education, University of Utrecht, P.O. Box 80.008, 3508 TA Utrecht, The Netherlands.

Liu, X.; Lesniak, K. Progression in children's understanding of the matter concept from elementary to high school. *J. Res. Sci. Teaching* 2006, *43,* 320–347. This very comprehensive study of children's understanding of chemistry consists of interviewing students from grade K–8 and grade 10 on the matter concept. The study was carefully planned and included in a pilot study. The general conclusions were that children progress from perceptual characteristics and uses and benefits to perceiving physical properties and change in grade 4 and up, to perceiving chemical properties and change in grade 5, chemical changes in grade 6, and finally to perceiving the particulate model of matter in grade 10.



Mike Ciesielski

Recommended Web Sites

http://www.chemistry.org/kids (accessed March 24, 2008). An excellent Web site sponsored by the American Chemical Society with a wide range of suggested activities for various grade levels.

http://www.stevespangler.com (accessed March 24, 2008). A Web site that was recommended by several teachers of all levels that has easy-to-use activities for all areas of science.

References

Abraham, M. R.; Williamson, V. M.; Westbrook, S. L. A Cross-Age Study of the Understanding of Five Chemistry Concepts. *J. Res. Sci. Teaching* 1994, *31,* 147–165.

American Association for the Advancement of Science (AAAS). *Atlas of Science Literacy;* National Science Teachers Association: Washington, DC, 2001.

AAAS. *Benchmarks for Science Literacy;* Oxford University Press: New York, 1993.

Griffiths, A. K.; Preston, K. R. Grade 12 Students' Misconceptions Relating to Fundamental Characteristics of Atoms and Molecules. *J. Res. Sci. Teaching* 1992, *29*, 611–628.

Harrison, A. G.; Treagust, D. F. The Particulate Nature of Matter: Challenges in Understanding the Submicroscopic World. In *Chemical Education: Toward Research-Based Practice*; Gilbert, J. K., Jong, O.D., Treagust, D. F., Van Driel J. H., Eds. Kluwer: Dordrecht, 2002; pp 189–212.

Johnstone, A. H. *Fashion, Fads, and Facts*. Paper presented at the American Chemistry Society Meeting, Washington, DC, September 1990.

Johnstone, A. H. The Development of Chemistry Teaching: A Changing Response to Changing Demand. *J. Chem. Ed.* 1993, *70*, 701–705.

Liu, X. Student Competence in Understanding the Matter Concept and Its Implications for Science Curriculum Standards. *School Sci. Math.* 2006, *106*, 220–227.
Liu, X.; Lesniak, K. Progression in Children's Understanding of the Matter Concept from Elementary to High School. *J. Res. Sci. Teaching*, 2006, *43*, 320–347.
Nakhleh, M.; Samarapungavan, A. Elementary school children's beliefs about matter. *J. Res. Sci. Teaching* 1999, *36*, 777–805.
Nakhleh, M., Samarapungavan, A.; Saglam, Y. Middle school students' beliefs about matter. *J. Res. Sci. Teaching* 2005, *42*, 581–612.
National Research Council. *National Science Education Standards;* National Academy of Science: Washington, DC, 1996.
Wolke, R. L. Forget chemistry: Letter to the Editor. *Chem. Eng. News* 2006, *36*, 3.