Grace A. Neff, Jennifer Retsek, Lola Berber-Jimenez, Nicole Barber, Monica Coles, Christina Fintikakis, and Brent Huigens

Bend it, Stretch it, Hammer it, Break it: Materials Chemistry Applied

Abstract

Making chemistry both accessible and interesting to middle and high school students can be difficult. Convincing middle and high school teachers that they will learn something new and applicable from a professional development workshop in chemistry can be equally challenging. This paper describes the use of material science as a means to enhance interest in basic chemical concepts. By making use of familiar materials, it seeks to reveal the applicability of chemistry to everyday life. Metals, semiconductors, and polymers were the materials at the heart of this course for secondary level teachers. Properties of these materials were investigated in hands-on activities and firmly connected to the bonding type and structure in each material through interactive discussion. The course itself will be described, and a few of the activities will be highlighted. Teachers' responses to daily surveys and final evaluations will also be discussed, and future directions will be addressed.

Introduction

As the study of matter, its properties, and its reactions, chemistry plays an integral role in every aspect of every life. However, chemistry can be a complex and abstract subject, and students often struggle with learning it. Research into misconceptions and problem solving in chemistry illuminates this difficulty (Bodner, 1991; Kind, 2004; Nakleh, 1992). The struggle with chemistry extends beyond the students to the teachers of chemistry – teaching an abstract, complex subject, and making it accessible, relevant and applicable to students, is challenging (Gabel, 1999). The authors know this from experience in teaching introductory chemistry to college students and hear this anecdotally from colleagues teaching in middle and high schools. Teachers' attitudes toward teaching chemistry can be just as critical to student success as their knowledge of the subject. "In all education, especially science, the teacher is the enabler, the inspiration but also the constraint. … their instructional behaviors are influenced by their attitudes towards science, a fact that does not go unnoticed by students" (Vaidya, 1993, p.63). Also, the middle and high school years are critical ones for science education. Studies have shown that as students get older, their attitudes towards science become less favorable (Fleming & Malone, 1983; Sorge, 2007). One such study indicated that science attitudes show a "precipitous drop" when students make the transition from elementary to middle school (Sorge, 2007). This particular study suggested that the observed changes in attitude may be connected to developmental changes in students and recommended further research (Sorge, 2007). Another study suggested that older students' inability to see themselves using science outside the classroom may be connected to their perception that science is about reading and lecture and not about performing activities (Barman, 1999). Moreover, students' attitudes toward science can be "most significant" in determining whether or not they will continue with further science study or choose science as a career (Osborne, 2003, p.1055).

With these issues in mind, a 40-hour professional development (PD) course was created for middle and high school teachers. The focus of this course was materials chemistry, an area rich in applicable content relevant to both teachers' and students' lives. In order for students to fully appreciate science and value learning it, science courses throughout K-12 grades need to clearly show the relevance of science taught in the classroom to everyday life (Barman, 1999). To make chemistry accessible by showing how it relates to materials used in everyday life, we placed the chemistry of bonding into the context of the resulting material properties. In just the last century, our society has become increasingly reliant on modern materials such as plastics, composites, and semiconductors, and all of these materials have extended the boundaries of our technological capabilities (Sass, 1998). The relevance of materials like these to students' everyday life is obvious, and this allows us to make chemistry more interesting and

Keywords: Materials chemistry, materials properties, chemical bonding

accessible. The connection between bonding type and observable material properties gives teachers a way to update their own knowledge and teach a basic concept with renewed interest and more applicability.

Figure 1 below illustrates the connection and flow of the concepts covered in this course. The materials themselves are the basis of this course – these are the observables that the teachers (and students) can relate to and connect to in their everyday lives. The materials studied were all solids, and, consequently, the bonding in solids and the theoretical basis of that bonding (band theory) are necessary components to the course. Structure and bonding are intimately connected and also determine properties of solids. Thus, the concepts come full circle to answer the question, "How is the bonding in a material related to or responsible for the observable properties?"

This course has been offered twice with a total of 26 teachers participating, and it is part of ongoing work between the Central Coast Science Project (CCSP) and teachers from partnership schools. The CCSP, one of 18 California Science Projects (CSP, 2009), is a collaborative endeavor between University science faculty and local school districts to improve science education for all students. The main presenters for the course were Cal Poly Chemistry faculty; collaborators from Materials Engineering (MATE) played a key role in the first incarnation of the course. Undergraduate chemistry and materials engineering students developed some of the background content and adapted several of the activities in the first year. The work of two of these students became their senior projects, which are required for graduation from this university (Barber, 2005; Coles, 2005).

The intention behind the course is not to "reinvent the wheel." All the parts of the course were already in existence. The course was based on the authors' teaching experience in and content from an engineering general chemistry course (Bailey, 2004). The activities were adapted from a variety of sources (see Table 1). Many of these activities had been developed for and used in classrooms, and the fundamental goal was that all the materials used would be familiar to teachers and students alike. For example, materials included metal wire and sheeting, plastic grocery and trash bags, and light emitting diodes (LEDs). The value of this program results from pulling all the program components together into a coherent package. Course content is interwoven throughout and strongly connected to the activities. The materials used in the activities were all readily available, and this allows the teacher participants to practice these activities before using them in their own classrooms. This enables them to see what works and to predict what might not work well with their students. A list of sources of materials was also given to teachers. Another valuable aspect of this professional development program is the presentation and facilitation of the course by content experts in a collegial setting. As university faculty, the authors bring a valuable level of expertise to the presentations, discussions, and activities. The faculty are readily available resources of knowledge for the teachers, and they are willing to answer questions and troubleshoot problems with the activities. Furthermore, the benefit that resulted from the collaborative nature of the course cannot be overstated. Teachers were brought together to meet and work with colleagues during the summer, which is an opportunity they do not have during the school year. The workshop setting is one of the main reasons that the whole package of this course is of much greater value than merely providing the participants with a description of the individual activities.

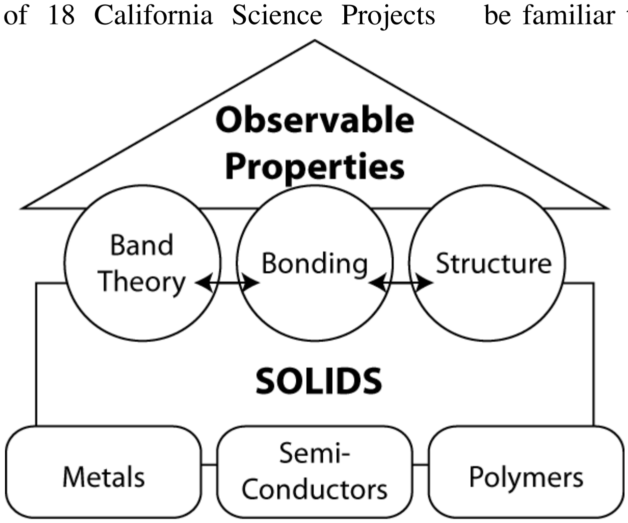


Figure 1: Connectivity of bonding, structure and observable material properties

Structure of the Workshop

In both years this course was taught, the majority of participating teachers were middle and high school teachers, and, in the second year, there were also a few elementary school teachers. These teachers were equally distributed between experienced teachers and newer teachers, and the average years teaching experience was approximately fifteen. Some of the high school teachers had strong chemistry backgrounds and were interested in learning new applications of their knowledge. Other high school teachers, as well as some of the middle school teachers and most of the elementary school teachers, were lacking in their chemistry backgrounds and were looking to increase both their content knowledge and their application skills. Both groups of teachers had strengths to bring to the course, as well as needs for the course to fill. Both years, teachers were asked to read a chapter on Materials Chemistry from a general chemistry text that was sent in advance (Gilbert, Kirss, & Davies, 2004). They were also sent an outline of the course in a daily schedule. In the first year of instruction, teachers started the program with a "crash course" in materials processing by visiting a materials engineering laboratory on campus and performing steel processing, metal and polymer tensile strength testing, cold working of metals, and a Charpy impact test (California Polytechnic State University [CPSU] Materials Engineering website, 2005). In year two, this portion was omitted (see Impact and Conclusions), and the course started with a Concept Inventory Pre-Test that had been developed by the authors using questions from an existing Materials Concept Inventory (Griffins & Krause, 2005) and from their own existing course materials. Both years, teachers were given a course packet that included background content on each topic covered and the instructions for the activities. The daily schedules consisted of alternating content presentations and corresponding activities.

Good professional development must include "activities that are teacher-centered, challenging, authentic and collaborative" (Daniels, Bizar, & Zemelman, 2001, p. 241), and this course was predicated on and evaluated based on that idea. In addition, involving participants in first-hand investigation of material properties is aligned with the constructivist approach to learning. This approach basically states that knowledge cannot be transmitted from teacher to learner, and, instead, the learner must actively acquire that knowledge so that the learning is more concrete when it is applied (Padilla, 1991). Thus, teachers worked in small groups (2-3) both years to carry out the activities. In year one, teachers also collaborated in these groups to adapt one activity for use in their classrooms. In year two, time was set aside for the groups to debrief together after most activities. Both years, teachers were given an evaluation at the end of each day, and then a final evaluation was given the last day of the workshop.

Content and Activities

Table 1 shows an outline of the content covered and examples of activities performed. In this course, basic bonding theory was approached in an applied manner by utilizing a perspective that investigates the ways that bonding type affects the observed material properties. The course was taught as if it were a rigorous, college-level class, regardless of the grade level at which the teachers taught. Even though these teachers, particularly at the middle or elementary school level, may never cover some of the topics, this high level of instruction is necessary. First of all, it helps teachers see the connection between the topics presented in the course and other, related topics. Also, in order for teachers to feel competent and be confident in answering any questions posed to them by their students, they must achieve a high level of understanding.

An important aspect of this course was that the activities had to use materials that were easily attainable from hardware stores, grocery stores, or online resources. The more "exotic" materials, like LEDs, were supplied to the teachers, and the source was identified. The equipment used to study some properties, like the conductivity probes, was either handmade in the lab by our students (Gadek, 1987) or purchased at minimal cost from an online source. Many of these activities were scaled-down versions of processing or testing techniques performed in industry or in university-level laboratories that had been adapted for use in the classroom. For example, cold-working and steel processing were accomplished using wires, and polymer tensile strength testing was accomplished using a variety of polymer samples like trash bags, along with ring stands, binder clips, and weights.

One example of a familiar type of material studied in great detail in this course was metals. Properties of metals, such as conductivity and malleability, were described as resulting from the delocalized nature of the bonding electrons in metallic bonding. In metallic bonding, no one metal nucleus holds the valence electrons strongly bound to itself, so these electrons are free to move about throughout the collection of atoms, and thus easily conduct both electricity and heat (Gilbert, Kirss, & Davies, 2004). This flexible electron

Table 1: Materials Chemistry Content Covered and Representative Activities

Content	Representative Activities	Demonstrated Material Property	Bonding Concept(s) Applied
Basics of Bonding	Melted Away[a]	Melting point	Differences in ionic and covalent bonding
	Metal or Nonmetal?[b]	Conductivity, malleability	Differences in metallic and covalent bonding
Basics of Solids	Solid State Models[c]	Structure of solids at atomic level	Bonding in solids
	Crystals Up Close[d]	Structure of solids at macroscopic level	Bonding in solids
Properties of Metals, Defects	Drop the Noodle[e]	Comparing heat conduction in metals	Metals conduct heat well due to delocalized nature of bonding electrons
	Metal Working & Strength[f]	Malleability and strength of metals	Metals are malleable and strong due to delocalized electrons and presence of defects
Band Theory	Exploring Conductivity Part 1[c,f]	Conductivity of materials as a function of temperature	Comparing conductors, semiconductors, and insulators
Semiconductors: LEDs	Exploring Conductivity Part 2[c,f]	Conductivity of semiconductors as function of temperature and composition	Conductivity of semiconductors depends on what it is composed of and on temperature
Polymer Basics and Reactions	Making and Recycling a Polymer[g]	Stretching and elasticity of different polymers	Cross-linking in polymers
Polymer Structure and Properties	Polymer Absorption[h]	Absorption properties of different polymers	Structure of polymer
	Tensile Strength Test[i]	Stretching force different polymers can withstand	Composition and structure of polymer
	Density Challenge[f]	Density of different polymers	Composition and structure of polymer

a original reference unknown

b Stanitski, C. L. (1998)

c Bailey, C. A., et al. (2005a; 2005b)

d Wynne (1997)

e Kardos (1996b)

f Department of Materials Science and Engineering, University of Illinois at Urbana Champaign. (1996a; 1996b; 1996c; 1996d; 1996e)

g Tosiani, T. (2009)

h Schug, T. (2003)

i Plastics Division of the American Chemistry Council (2004).

"glue" holds the atoms together yet allows them to move when force is applied, which results in malleability. The latter is a simplification of a more in-depth explanation, one that explains malleability as resulting from the presence of dislocations in the metal lattice (Tilley, 2004). This more complete explanation was also explained to the teachers in this course, even though it may be well above the level of detail of most middle or high school classes. It was left to the participants to decide how to adapt these explanations for use with their particular students.

To illustrate metal properties, teachers completed several different activities, some of which are shown in Table 1. For example, heat conduction is well illustrated by comparing how different metal, plastic, and wood bars or rods conduct heat from hot water along their length in order to melt wax, margarine, or peanut butter and release a noodle that the substance had been adhering to the rod (Kardos, 1996b). The property of malleability was investigated in the Tensile Strength Activity (Dept. of Material Science & Engineering Univ. of Illinois Champaign-Urbana 1996b; Hennon 2004). In this activity, different metal wires or rods of the same gauge are clamped onto a ring stand and a small paper cup is suspended from the end. Metal washers of known mass are then added to the cup until the wires are permanently deformed by the stress. This lab can be very quantitative in that the force exerted by the washers could be calculated, as could the displacement experienced by the wire or rod (Hennon, 2004). By plotting the mass applied as a function of displacement experienced by the wire, both the stiffness and the yield strength of the metals could be determined (Dept. of Material Science & Engineering Univ. of Illinois Champaign-Urbana 1996e). This lab can be simplified or adapted into a simple, qualitative comparison of different metals or a comparison between properties of metal, polymer, and wood that is performed in the same manner without any calculations. The latter comparison of metal, polymer, and wood can be done using rulers held in place with a clamp and hanging a fixed distance from the edge of a table, with the force applied being accomplished using metal washers that fit over the end of the ruler.

Polymers were also studied in great detail, and a variety of activities were useful in illustrating properties of these materials as a function of the bonding and/or structure in the polymers. For example, tensile strength was examined both quantitatively and qualitatively using low density polyethylene (LDPE) dry cleaning garment bags and high density polyethylene (HDPE) grocery bags, as well as other plastics like Saran wrap (polyvinylidene chloride, PVDC) (Plastics Div. of American Chemical Council, 2004). By using binder clips to attach pre-cut strips of the plastic to a ring stand and suspending washers from another binder clip at the bottom, this activity can have a strong quantitative component. Here comparisons could be made of either the amount of force required to permanently deform different materials, or of the distance the samples stretch under application of a set force. A more qualitative version of this investigation is to have participants simply compare how far they can stretch the different materials by hand before they break.

Discussions here focused on how the differences in chemical composition (PE vs. PVDC) or physical properties like density (LDPE vs. HDPE) result in different material properties like tensile strength. Polymer molecules are composed of mostly carbon atoms bonded to each other in long chains, with other atoms, such as hydrogen, bonding to carbon as well to give each carbon four bonds. The bonding here is covalent, which is localized sharing of electrons between two atoms. The carbon atoms in this "backbone" can rotate freely, and that is what makes these polymers flexible (Sass, 1998). Increased strength or stiffness of polymers like HDPE is achieved by stacking and folding neighboring chains to give a more ordered, nearly crystalline substance in which deformation is achieved through stretching the bonds along the carbon backbone (Sass, 1998; Tilley, 2004). The two PE polymers are composed of the same basic chemical "parts" or monomers, but the polymer chains in the low density material are branched and thus cannot pack together tightly. This results in a lower density material that is flexible but doesn't stretch as much as the higher density material (Lajeunesse, 2004). The HDPE polymer chains are not branched, so they pack more tightly and result in a more rigid material that still stretches and has a tensile strength greater than that of LDPE. (Tilley, 2004).

Impact and Conclusions

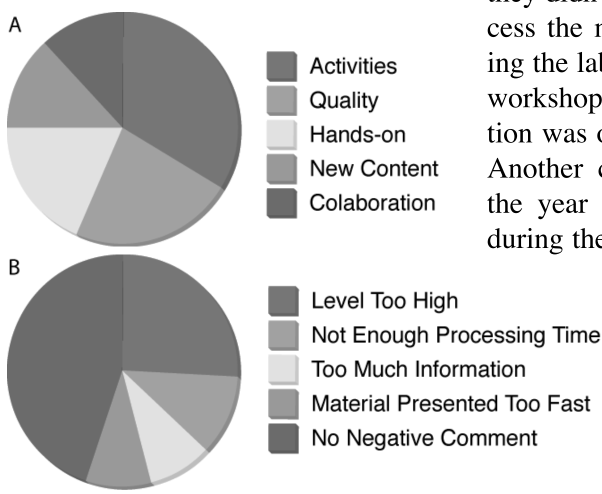
This workshop was delivered twice to a total of 26 teachers from 20 schools and 10 districts. Eleven schools were located in districts on the Central Coast of California while 6 more were in Southern California and three were in Central California. Thus, the geographical reach of these workshops was broad. Four of the teachers were elementary, 7 were middle school, 13 were high school teachers, and the remaining two were district science coaches. The potential impact of this workshop on students is significant. With an estimate that the elementary teachers each had 35 students in their classes, and the middle and high school teachers had 6 periods of 40 students each, these workshops had the potential to affect over 5,000 students.

To gauge the impact on individual teachers, daily evaluations were used, and summative assessment was achieved via a final evaluation. The daily evaluations were open-ended and asked teachers to comment on what they liked and disliked about the daily lessons. There were, of course, a wide variety of responses, but systematic coding and analysis of comments revealed that five themes were mentioned most frequently (Strauss & Corbin, 1998). These responses are shown in Figure 2A. The predominant comment indicated that the teachers liked the activities they performed (~34%). The high quality of the presentations and presenters was the next most common response (~23%), with the hands-on aspect of the workshop also being popular (~19%). Teachers also appreciated learning new content (~13%) and being able to work with other teachers (12%). All of these comments indicate achievement of our own teaching goals and demonstrate a degree of success of the course.

A similar analysis was performed on the responses about dislikes. There were only approximately a third as many responses to this question as there were to the previous question

(Figure 2B), and this is an encouraging observation. No one response was repeated at a rate greater than 26%. The most often repeated comment (26%) was that the workshop material was presented at too high a level, and 11% indicated that not enough time was allowed for the teachers to thoroughly digest the material presented. The smallest percentage (9%) of the comments complained that too much information was presented and also that it was presented at too fast a pace. Such comments were expected, due to the varied science backgrounds of the participants and the different levels at which they teach. To address these concerns in future iterations of the course, less material may be presented or the workshop may be extended to a longer period of time. However, rigor of the presented content will not be lessened, because it is important that teachers understand the content at a higher level than their students, in part to avoid propagation of misconceptions (Nakleh, 1992).

Figure 2: Results of systematic coding and analysis of responses to the Daily Evaluaquestions A) "What I liked," and B) "What I didn't like"



Insights gained in year one from the daily evaluations were useful in further developing the format of the course for year two. In year one, teachers indicated that they enjoyed using the industrial scale equipment in the MATE lab and valued the hands-on aspect of this part of the course, but several also indicated that it was a bit overwhelming and they didn't have enough time to process the material in spite of receiving the lab manual in advance of the workshop. For this reason, this section was omitted in the second year. Another change that resulted from the year one evaluations was that, during the second year, time was set aside after most of the activities for debriefing.

The final evaluations asked teachers, among other things, if the workshop met their expectations and if there was something they learned that they would use in their classrooms. Overall the responses to both questions were positive, with 39% of respondents stating that the workshop met their expectations, and the remaining 61% said the workshop exceeded their expectations. A majority of respondents (65%) stated they would use at least some of the activities but were not specific as to which ones. About 26% commented that they learned more about bonding than they ever had, particularly metallic bonding, while 22% commented favorably about learning about polymers and the same percentage appreciated learning about the properties of the materials.

These final evaluations indicate overall satisfaction by the participants, which further indicates that the course was successful. Future iterations will include pre- and post-tests so that more quantitative data can be obtained (a concept inventory was used only the second summer). To evaluate the long-term effect of the course on participant teaching, follow-up evaluations with past participants are planned. These evaluations will ask questions regarding continued use of activities and pinpoint which activities are still being used. This will help us hone the material and make the course as useful to teachers as possible. New content and activities on other materials like ceramics, wood, paper, and fibers will also be developed for future workshops.

References

Barber, N. (2005). Chemistry essentials secondary: A workshop provided by the Central Coast Science Project. Senior Project for Department of Chemistry and Biochemistry, San Luis Obispo, CA: California Polytechnic State University.

Barman, C. R. (1999). Completing the study: High school students' views of scientists and science. *Science and Children, 36*(8), 16-21.

Bailey, C. A., (2004). Studio chemistry at Cal Poly. Retrieved from http://chemweb.calpoly.edu/cbailey/Studio/

Bailey, C. A., et al. (2005a). Solid state modeling. In *Chemistry 124 online laboratory manual*. San Luis Obispo, CA: California Polytechnic State University. Retrieved from http://chemweb.calpoly.edu/chem/124/

Bailey, C.A., et al. (2005b). Conductivity. In *Chemistry 124 online laboratory manual*. San Luis Obispo, CA: California Polytechnic State University. Retrieved from http://chemweb.calpoly.edu/chem/124/

Bodner, G. M. (1991). I have found you an argument. *Journal of Chemical Education, 68*(5), 385-388.

California Polytechnic State University (CPSU) Materials Engineering Department. (2005). MATE 215 laboratory course. Retrieved from http://mate.calpoly.edu/

California Science Project. (2009). Retrieved from http://csmp.ucop.edu/csp/index.php

Coles, M. (2005). Improving science education: Using polymers to make chemistry fun, interesting and accessible to teachers and their students. Senior Project for Department of Chemistry and Biochemistry, San Luis Obispo, CA: California Polytechnic State University.

Daniels, H., Bizar, M., & Zemelman, S. (2001). *Rethinking high school,* Portsmouth, NH: Heinemann.

Department of Materials Science and Engineering, University of Illinois at Urbana Champaign. (1996a). Estimating semiconductor band gap using LEDs. In *MAST module: Materials science and technology*. Retrieved from http://matse1.mse.uiuc.edu/

Department of Materials Science and Engineering, University of Illinois at Urbana Champaign. (1996b). Hot and cold: Temperature and resistance of electronic materials. In *MAST module: Materials science and technology.* Retrieved from http://matse1.mse.uiuc.edu/

Department of Materials Science and Engineering, University of Illinois at Urbana Champaign. (1996c). Making metals strong. In *MAST module: Materials science and technology.* Retrieved from http://matse1.mse.uiuc.edu/

Department of Materials Science and Engineering, University of Illinois at Urbana Champaign. (1996d). Plastics the second time around. In *MAST module: Materials science and technology*. Retrieved from http://matse1.mse.uiuc.edu/

Department of Materials Science and Engineering, University of Illinois at Urbana Champaign. (1996e). Stretching wires. In *MAST module: Materials science and technology.* Retrieved from http://matse1.mse.uiuc.edu/

Fleming, M. L. & Malone, M.R. (1983) The relationship of student characteristics and student performance in science as viewed by meta-analysis research. *Journal of Research in Science Teaching,* 20(5), 481-495.

Gabel, D. (1999). Improving teaching and learning through chemistry education research: A look to the future. *Journal of Chemical Education,* 76(4), 548-554.

Gadek, F. J. (1987). Easily made electronic device for conductivity experiments. *Journal of Chemical Education, 64*(7), 628-629.

Gilbert, T .R., Kirss, R. V., & Davies, G. (2004). *Chemistry: The science in context*, 1st Edition. New York, NY: W. W. Norton & Company.

Griffins, R.B. & Krause, S. (2005). Materials concept inventory. Obtained through personal correspondence with the authors.

Hennon, S. (2004). Can you handle the stress? *Cornell Center for Materials Research (CCMR) Research Experience for Teachers*. Retrieved from http://www.ccmr.crnell.edu/education/modules/retmodules.html

Kardos, T. (1996a). 20. Metals conduct heat. *75 Easy chemistry demonstrations,* Portland, OR: J. Weston Walch.

Kardos, T. (1996b). 26. Different metals and nonmetals conduct heat differently. *75 Easy Chemistry Demonstrations,* Portland, OR: J. Weston Walch.

Kind, V. (2004). *Beyond appearances: Students' misconceptions about basic chemical ideas*. London: Royal Society of Chemistry.

Lajeunesse, S. (2004). Plastic bags. *Chemical and Engineering News, 82*(38), 51. Retrieved from http://pubs.acs.org/cen/whatstuff/stuff/8238plasticbags.html

Nakleh, M. B. (1992). Why some students don't learn chemistry. *Journal of Chemical Education, 69*(3), 191-196.

Osborne, J. (2003). Attitudes towards science: A review of literature and its implications. *International Journal of Science Education, 25*(9), 1049-1079.

Padilla, M.J. (1991). Science activities, process skills, and thinking. In *The psychology of learning science*. Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Plastics Division of the American Chemistry Council (2004). *Hands on plastics: A scientific investigation kit*. Retrieved from http://www.americanchemistry.com/hops/activities/index.html.

Sass, S. L. (1998). *The substance of civilization: Materials and human history from the stone age to the age of silicon*. New York, NY: Arcade Publishing.

Schug, T. (2003). Superabsorbant polymer demonstration. *Cornell Center for Materials Research (CCMR) Research Experience for Teachers*. Retrieved from http://www.ccmr.crnell.edu/education/modules/retmodules.html

Sorge, C. (2007). What happens? Relationship of age and gender with science attitudes from elementary to middle school. *Science Educator, 16*(2), 33-37.

Stanitski, C. L.(Ed.). (1998). Metal or nonmetal? In *Chemistry in the community* (pp. 108-110). Dubuque, IA: Kendall Hunt Publishing Company.

Strauss, A., & Corbin, J. (1998). *Basics of qualitative research: Techniques and procedures for developing grounded theory*. Thousand Oaks, CA: SAGE Publications, Inc.

Tilley, R. J. D. (2004). *Understanding solids*. West Sussex, England: John Wiley & Sons, Ltd.

Tosiani, T. (2009). Silly putty – Goop, GAK, gluep. In *Chemistry experiments, projects and demonstrations you can do at home*. Retrieved from http://homexperiment.com//silly-putti.html

Wynne, R., Johnson, M., & Anderson, S. L. (1997). Crystals up close. In *Experiencing chemistry*. Portland, OR: Oregon Museum of Science and Technology.

Vaidya, S.R. (1993). Restructuring elementary and middle school science for improved teaching and learning. *Education*, *114*, 63-70.

Author 1 is an Associate Professor of Chemistry, Department of Chemistry and Biochemistry, California Polytechnic State University, San Luis Obispo, California, 93407. Correspondence concerning this article may be sent to gneff@calpoly.edu.

Author 2 is a Lecturer of Chemistry, Department of Chemistry and Biochemistry, California Polytechnic State University, San Luis Obispo, California, 93407.

Author 3 is the Department Chair, Department of Liberal Studies, California Polytechnic State University, San Luis Obispo, California, 93407.

Acknowledgments: The authors gratefully acknowledge the collaboration with Dr. Dave Neibuhr and Mr. Tim Orling and their work with teachers in the MATE 215 lab in 2005. That experience was invaluable for the teachers and authors. The authors sincerely appreciate and thank the teacher participants for their input, comments, and enthusiastic participation in these workshops. We thank our technical staff members Paul Shires and Shelley Zoff for their assistance and patience. We acknowledge the Department of Chemistry and Biochemistry at Cal Poly SLO for use of laboratory facilities and the Studio classroom, and the Materials Engineering Department for use of the MATE 215 laboratory. We also gratefully acknowledge Seth Bush for his preparation of the figures in this paper. Lastly, we thank the Long Beach Unified School District for providing matching funds for their teachers, and we further acknowledge funding from the University of California Office of the President via the California Science Project.

The work described in this paper was made possible by California Science Project funding from the University of California Office of the President. The Long Beach Unified School District also provided matching funds for their teachers.