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Student-centered, Nanotechnology-enriched Introductory College Chemistry Courses for Engineering Students*

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Nanotechnology provides numerous examples of materials and devices that can be incorporated into the classrooms and laboratories of introductory college chemistry courses. These examples illustrate tools used to investigate and shape matter at the nanoscale and materials and devices whose properties depend on nanoscale control. Engineering students in these courses can benefit by seeing applications of chemical and physical principles in modern technological contexts and by developing skills that will enable them to participate in fields that involve nanotechnology. Pedagogical methods and assessment and evaluation tools that reflect inquiry-based approaches to instruction can be aligned with nanotechnology exemplars in these courses.

INTRODUCTION

NANOTECHNOLOGY is providing unprecedented opportunities for the research and technology communities to create materials and devices with customized properties having the potential to revolutionize many aspects of our daily lives. The US National Nanotechnology Initiative, which represents a commitment to promote infrastructure and new technologies in this broadly defined field, is receiving widespread attention [1, 2]. A strong educational infrastructure that prepares a diverse group of talented engineering students to work in nanotechnology is a critical element of technical workforce development. In this article we summarize initiatives at the University of Wisconsin-Madison (UW) and Christian Brothers University (CBU) aimed at enhancing the introductory college chemistry courses taken by engineers to better prepare them for work in nanotechnology-related fields.

Chemistry is a natural discipline for incorporating nanotechnological examples, because it is fundamentally the study of matter at the atomic scale, the nanoscale. The traditional American college chemistry course, however, has tended to focus on small molecules in the gas phase and in solution. In the past decade, solids have become more prominently represented in such courses, permitting exploration of materials science and nanotechnology issues [3]. In addition to broadened exposure to classes of materials, like polymers, semiconductors, metals, and ceramics, there is the opportunity to address nanoscale issues such as quantum size effects, the importance of surface-to-volume ratio, and scalability of physical phenomena. In many respects, the fields of chemistry and materials science merge at the nanoscale, as evidenced by the teams of scientists and engineers actively working in nanotechnology.

Chemistry is also an appropriate venue for nanotechnology because it is a curriculum 'pressure point' in the American system of post-secondary education and directly impacts human resources needed for nanotechnology. Many college students take an introductory chemistry course as a requirement for an engineering major or to fulfill a distribution requirement. Their attitudes and career trajectories are often shaped by their experiences in this course.

Increasing evidence in the past decade indicated that college chemistry courses were often unpleasant experiences for the students taking them. The courses were frequently perceived as irrelevant by engineers, relying as they did on old examples and technologies. There was little emphasis on how information was obtained and on the scientific method, the process of scientific inquiry. Students often noted the lack of a storyline: The course seemed to be compartmentalized with little linkage among the topics covered.

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The culture of a traditional American college chemistry course was also off-putting to many students, particularly in the environment of large research universities where classes often number several hundred students. Such courses have been described as dehumanizing, with students having little personal contact with instructors and with classmates, with whom they are competing for a limited number of good grades using a 'curved' grading system [4]. These courses have created a culture that promotes the 'weeding out' or 'filtering' of students. In some cases, students planning to major in engineering have been sufficiently alienated by their experience in chemistry that they switched to other fields [5]. As the negative effects of this approach on many students were documented, some instructors began using cooperative learning methods and more sophisticated assessment and evaluation tools with the intent of turning these courses into pumps rather than filters. There is considerable evidence now that these approaches enhance student learning, persistence, and attitude. They have also resulted in more integrated approaches to teaching chemistry courses [3, 6, 7].

The nanotechnology curricular experiments that we describe at CBU and UW illustrate conditions imposed by two very different venues. CBU has small classes of 20–30 engineering majors (civil, electrical, and mechanical). UW has large 250–350 student lecture sections that are offered as mathematics-intensive classes designed for science and engineering majors, and as less mathematical classes for non-technical majors needing to satisfy a college distribution requirement. The fraction of these classes populated by engineering majors might typically range from 20–40%. In succeeding sections of this article we describe some of the content we have used related to nanotechnology and the pedagogical and assessment and evaluation approaches we have employed in these classes.

CONTENT

Recent advances in nanotechnology, technology at the scale of individual atoms, can be used to create an engaging storyline for college chemistry courses. Nanotechnology has enlivened these courses by providing modern, high-tech multidisciplinary examples of fundamental chemical principles that are relevant to engineering students. Rather than attempt to be exhaustive, we present a few examples that illustrate tools used to investigate and shape matter at the nanoscale and materials and devices whose properties depend on nanoscale control. A complete listing of instructional resources that we and others have developed for teaching about nanotechnology is available at several websites, for example [8, 9]. Collectively, these resources can be used to develop the nanotechnology-based storyline of chemistry as being atoms and the electrons that hold the atoms together.

Nanotechnology permits direct imaging of atoms using scanning probe microscopy (SPM) techniques. SPM can be introduced with a simple macroscale demonstration using a common refrigerator magnet (RM). A strip cut from the RM serves as a probe tip. When the tip is scanned across the unprinted surface of the RM, different forces are felt depending upon the direction in which the tip is scanned, enabling a student to infer the magnetic pole arrangement on the back of the RM. This simple macroscale experiment enables students to make a connection conceptually to the use of an atomically sharp probe tip and to atomic-scale rastering. The macroscale-nanoscale comparison helps students to appreciate the key elements of the SPM experiment. This demonstration can be viewed on the Web [10–12]. LEGOs have been used to build a scanning version of the atomic force microscope [13]. We have also brought examples of SPM images into our classes using resources like the IBM gallery [14].

Many crystalline metals and minerals figure prominently in nanotechnology. We have developed a solid-state model kit that permits facile construction of nearly 100 common crystal structures, each in a few minutes. The kit, which is distributed at cost by the Institute for Chemical Education (ICE), comprises bases, templates, rods, and spheres, whose diameters are in radius ratios [15]. A typical structure constructed with the kit is shown below in Fig. 1.

Both CBU and UW use a laboratory experiment in which students construct unit cells of common metals (e.g. face-centered cubic and body-centered cubic), and minerals (e.g. rock salt and diamond)

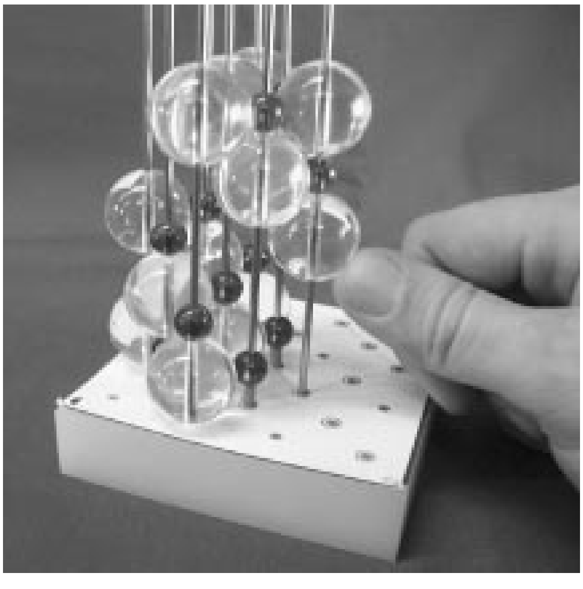

Fig. 1. The rock salt (NaCl) structure, built with the ICE Solid State Model Kit, showing opposing sheets of sodium and chloride ions that are revealed by lifting a bottom corner sphere of the unit cell.

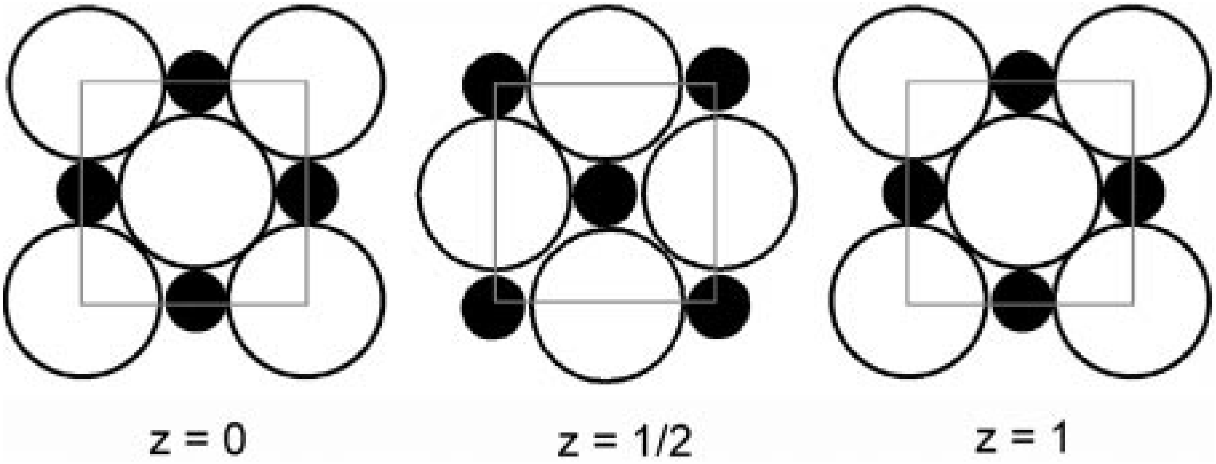

Fig. 2. A layer sequence for NaCl in which open circles represent chloride ions and filled circles represent sodium ions. The squares define the boundaries of the unit cell. The value of z represents the altitude of the unit cell at which centers of atoms are found; the floor of the unit cell is represented by z = 0 and the ceiling by z = 1.

and then examine the physical and chemical properties of solids having these structures. Examples include cleaving rock salt by striking a sample with a spatula and writing on glass using a diamond-tipped scribe [16]. Besides permitting students to develop an appreciation for the three-dimensional structures of these solids, the kits allow various surfaces to be explored that influence nanoscale behavior. Use of layer sequences like that shown for rock salt in Fig. 2 permits three-dimensional structures to be presented on a sheet of paper, blackboard, or projection display [16, ch. 3 and 5]. In our experience, while computer-generated images can show these structures, building them layer by layer and lifting portions to peek inside provide an important tactile component to understanding the structure.

Another aspect of a structure is the stoichiometry or chemical formula. Layer sequences allow quick counting of the unit cell contents. For example, there are $(8/8) + (6/2) = 4$ Cl^- ions and $(12/4) + 1 = 4$ Na^+ ions in the unit cell of Fig. 2. Layer sequences provide students with the means to record their observations of these three-dimensional structures in a two-dimensional format.

These structures also provide an opportunity for introducing another nanotechnology tool, X-ray diffraction. At UW, we use a laboratory experiment in which a scaled-up version of this experiment is conducted with pocket lasers and 35-mm laser-written, photographically-reduced slides. The slides contain a variety of arrays that mimic the packing of atoms in common metal and mineral structures. Students can measure the feature spacings on the slide using a plastic ruler and hand lens, then compare this value with that obtained in a simple diffraction experiment using the Fraunhofer equation. This inquiry-based approach permits students to explore the technique and appreciate the manner in which structural information is acquired from diffraction data. CBU uses the experiment more qualitatively as a classroom demonstration.

More complete descriptions of the experiment have been published, and optical transform kits with dozens of arrays are available through ICE. One set of arrays enables students to investigate how Rosalind Franklin's diffraction data led to the deduction that the structure of DNA is a double helix [16–18].

Nanoscale materials can easily be prepared in the laboratory to illustrate synthetic methods. A particularly popular experiment we have conducted is the preparation of ferrofluids, comprising nanoscale magnetite particles that are suspended in water by means of a surfactant. This is a rich experiment that can be used to illustrate principles of stoichiometry, oxidation state, crystal structure, magnetism, and surfactant chemistry [19, 20]. Samples prepared by students will produce eye-catching spikes in the presence of a strong magnet (Fig. 3).

Movies of the preparation of this material and its magnetic response are available [19, 20]. More

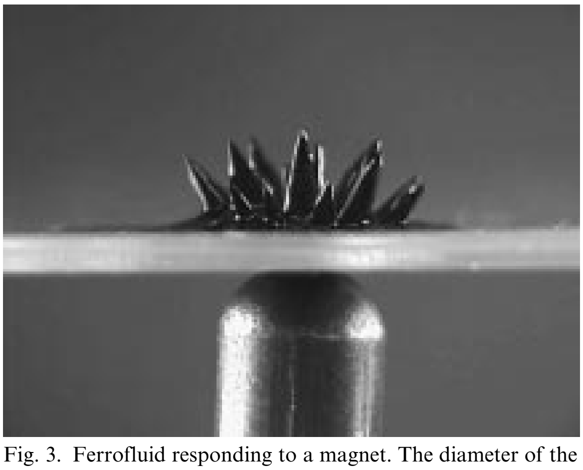

Fig. 3. Ferrofluid responding to a magnet. The diameter of the cylindrical magnet is approximately 12 mm.

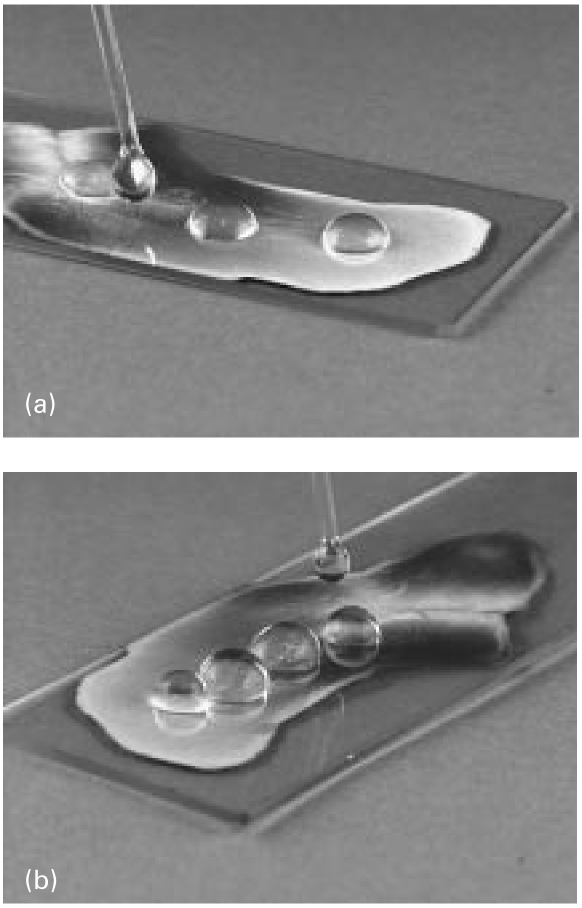

Fig. 4. Droplets of water on a silver film (a) before and (b) after adsorption of a monolayer of decanethiol. Water beads form on the more hydrophobic monolayer-coated surface.

generally, the experiment provides an opportunity to talk about applications that range from computer hard disk drives to loudspeakers to experimental work on magnetically-controlled drug delivery.

An example of nanoscale self-assembly is the formation of monolayers. Using a silver substrate, decanethiol molecules will spontaneously form a monolayer when adsorbed onto this surface. When a water droplet is placed on the monolayer-coated surface and the bare silver surface, a change in its contact angle can be easily observed (Fig. 4) [21].

Movies are available on the web of this and other nanoscience experiments, including preparation of micelles, colloidal gold, nanoparticle titanium dioxide-based solar cells, and F-centers [21].

The organizing template of chemistry is of course the periodic table. This can be introduced as a design tool for engineering students through light emitting diodes, LEDs. The nanoscale architectures used to create these devices are revolutionizing the lighting and display industries, as LEDs are increasingly seen in traffic and vehicle lights and in large area message boards with dynamic displays. From a chemical perspective, LEDs provide a wonderful means to link chemical composition with structure and spectroscopy, as compositional variations and quantum wells are used to tune the color of the LED and enhance the efficiency of these devices [22, 23]. Both UW and CBU carry out an experiment in which students solder an LED circuit and use it to explore trends in color, applied voltage, and diffraction spot spacing with respect to chemical composition. Dunking the LEDs in liquid nitrogen provides a means for assessing the temperature dependence of the band gap energy. A module that permits an extensive exploration of this technology over a two- to three-week period is available [24, 25].

In addition to the examples cited above, resources are available for many other technologies that are increasingly being used in nanotechnology. For instance, CBU has developed a laboratory experiment in which students dissect an inexpensive watch with a liquid crystal display. They measure the melting point of the liquid crystal and explore aspects of optical polarization and the lighting of feature segments with reference to engineering considerations. Resource materials are available for amorphous metals, nuclear magnetic resonance spectroscopy, giant magnetoresistance (GMR) effects, self-assembly of components to make larger structures, and materials with negative Poisson's ratios [21].

PEDAGOGY

As noted above, content should not be considered in isolation but as part of the entire culture of the course. Incorporation of nanotechnological examples is compatible with strategies that are being employed to make courses more user-friendly and more focused on student-centered learning. Both UW and CBU are using absolute grade scales: students learn at the outset of the course what the quantitative performance expectations are for achieving each grade. These quantitative measures can be lowered if the class performs below expectations, but cannot be raised. In this way students are encouraged to help one another, as there is no curving that restricts the number of desirable grades.

There are a variety of mechanisms that can be used to promote cooperative learning among students. A method that has worked well at UW and CBU is the use of ConcepTests [26–29]. A booklet and videotape are available that show how a class can be engaged in learning concepts by being asked focused questions, many related to nanotechnologies, with a choice of answers in a lecture setting. The class has a chance to vote on the correct answer by show of hands or signs, to persuade their neighbor(s) of its correctness, and to vote again. This technique provides real-time feedback for the instructor and gives students an opportunity to use the language and concepts of the field and to learn from one another.

ConcepTests highlight an important feature of course design, which is to identify skill objectives. For our courses at UW and CBU we identified the following as skills we wished to enhance through our choice of content and pedagogical methods:

- teamwork;
- verbal and written communication;
- nanoscale-through-macroscale descriptions of matter;
- visualization in three dimensions;
- facility with creating and interpreting graphs and tables;
- comfort with electronic tools like email, the web, and spreadsheets;
- analogies among chemically-based systems;
- critical thinking skills.

It is important to recognize that new opportunities are continuously emerging in pedagogical methods because of new technologies. For example, we have experimented with placing movies of laboratory experiments on the web. From preliminary feedback using the ferrofluid laboratory, we found that students responded overwhelmingly with enthusiasm, noting that they have a better sense of what is to be done when they arrive at lab. Similarly, some colleagues are using ConcepTests not with a show of hands or sign responses, but with touchpads that provide instant histograms of class understanding.

From the perspective of support structures, many students have benefited from participating in learning communities. At UW, students could enroll in sections with exclusively other engineering students for chemistry, math, and/or introductory engineering courses. These sections performed quite well. Women students participating in such a community (WISE: Women in Science and Engineering) were the top-performing section during several years in which the course was taught.

ASSESSMENT AND EVALUATION

It is well documented that assessment drives student learning [6]. In constructing our courses we have tried to develop assessment tools that are aligned with our goals for student achievement and the pedagogical methods that we are using. At UW this has led to a strong reliance on problem sets and short essay examinations that measure whether students can apply key concepts to new situations and clearly articulate their reasoning. An example might be to design an LED that will emit light of a particular energy from a plot of band gap energy versus composition.

For laboratory experiments we have used prelab quizzes to ensure that students are prepared and have thought about the issues to be investigated. Both CBU and UW have used WebCT [30]. This course management tool not only facilitates handling of student grades and course materials, but it can be also used to administer these quizzes. We have used scoring rubrics for grading laboratory reports in which we specifically identify criteria for achieving the highest grade and the kinds of deficiencies that will result in lower grades.

Through the National Institute for Science Education a suite of tools for assessment of classroom learning in college science, mathematics, engineering and technology courses is now available [6]. In addition to ConcepTests, portfolios, interviews, scoring rubrics and concept maps are some of the many tools that can be used to provide sharper measures of student learning.

Technology is making it easier to collect metrics for evaluation purposes. Measures by which classes can be evaluated include attendance, attitude, retention and throughput, and enrollment and performance in subsequent classes. Class attendance in instances when it is optional is a measure of class interest. At UW and CBU average class attendance increased from about 60% in the middle of the school year to about 80–90% with changes in content and pedagogical methods as outlined above. Attrition dropped from about 20–30% to about 5%. At UW, the net effect was a doubling of students taking the sequel to the initial introductory course, from about 200 to 400 students. We were able to demonstrate, too, at UW and CBU, that students in the nanotechnology- and pedagogically-modified course did as well or better statistically than students taught with traditional approaches, and over significantly larger numbers of students.

Using a web-based tool at UW for assessing attitude, students were generally more enthusiastic about the course and about recommending it to others [31]. UW has recently developed database management systems that will make it relatively easy to track subsequent enrollment and performance patterns. The databases can also identify evidence of differential impact, enabling instructors to adjust their courses so that students from all demographic groups can be successful.

CONCLUSION

In summary, nanotechnology is providing a rich set of new examples for introductory college chemistry courses. Because they are related to materials and devices that are changing the way we live and work, they can act as 'hooks' to capture the interest of engineering students taking these courses. When coupled with informed pedagogical, assessment, and evaluation practices, nanotechnology-enriched chemistry courses have the potential to enhance the knowledge and skills that engineering students will take from these classes and to recruit a diverse group of talented students into careers in nanotechnology.

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