Designing and Reporting Experiments in Chemistry Classes Using Examples from Materials Science: Illustrations of the Process and Communication of Scientific Research W

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Calls for reform in chemistry courses often emphasize the need to incorporate more experience with the process of research and with effective written communication (*1*). Inquiry-based laboratories provide excellent models for encouraging students to pose and answer questions that lead to the discovery of important physicochemical relationships (*2*), and a variety of programs involving more extensive scientific writing have been reported (*3*). The importance of these curriculum elements was recognized in a Carnegie Foundation report exhorting research universities to ensure that all students have some opportunity to learn about the scientific method through direct experience (*4*). Many undergraduates do have an opportunity to participate in original research and to use the scientific method, but the sheer numbers of students relative to the number of instructors can make it a daunting prospect to ensure the accessibility of this experience to all students. Some successful approaches based on service learning and through piecewise contributions by students to a large project have been reported (*5, 6*).

Overview

This paper describes an approach toward reaching these objectives that we have tested in an inorganic chemistry course comprising roughly three dozen juniors, seniors, and graduate students. Based on engaging demonstrations from materials science, students propose quantitative experiments, conduct them, and summarize them in a scientific article and a press release. As will be shown, these experiments lend themselves to variations that can be performed quantitatively and relatively quickly—even during a one- to two-hour period. Most experiments proposed by students were straightforward extensions of the demonstrations. Some had been previously reported in the literature, but even for these, students independently developed their own experimental protocols. Some experiments were, to our knowledge, completely original. A sampling of experiments is described in a section below.

Through a campus Writing Fellows program, undergraduates who had demonstrated good writing skills were paid modest sums to work with students in the class on their writing skills (*7*). Although the Writing Fellows were not chemistry majors, they edited early drafts of the student reports and press releases, providing constructive feedback to both students and instructors. Additionally, each student in the class served as an editor for a classmate, providing early valuable technical feedback on the reports (*8*).

Procedure

Students were given a list of roughly a dozen topics from which their original experiment could be developed, a detailed description of the report and press release expectations, and a schedule (*8*). The topic list was constructed around NiTi shape-memory alloy, high-temperature superconductors, amorphous metal, ferrofluid, optical transforms, graphitic electrical conductivity, a nuclear magnetic resonance simulator, and polydimethylsiloxane (PDMS) elastomer (*9*). After brief descriptions and demonstrations of each topic in class, students were directed to a variety of other resources, including a Web site that provided additional background information on each topic (*9*). As many as four students could sign up for a given topic, but each worked individually to develop his or her own experiment.

Students had about a week to propose an experiment that lent itself to quantitative data collection based on the topic of their choice. The instructor (ABE), postdoctoral associate (KJN), and graduate teaching assistant (CGW) then identified and acquired components required to conduct the proposed experiments safely, or worked with the student to modify his or her proposal to a form in which the experiment could be carried out. Laboratory space was secured and most students carried out their experiment during a designated lecture period under staff supervision. (The class currently does not have a laboratory associated with it.) Students who were absent, needed more time, or realized afterward that they wanted to modify their experiment made arrangements to continue their experimentation at another time that was mutually convenient.

After their experiments were completed, students had a week to prepare a first draft of their report in archival journal format (introduction, experimental section, results and discussion, and conclusion). They also prepared a one-page press release intended to describe their work to a nontechnical audience. Both the report and the press release were submitted to their Writing Fellow and to a classmate (who worked on a different topic) for feedback on writing quality and technical accuracy. The revised papers were then submitted to the instructors. A satisfactory grading scheme was based on seven equally weighted criteria, which included experimental design and execution, the research paper (content, organization, style, response to reviewers' comments), the press release, and editing of the classmate's paper and press release. The teaching assistant and instructor independently graded the assignment.

Feedback from students was generally positive, and many noted that this was the first time they had had an opportunity to conduct a research project of their own design. Even many of the students who had done some research had not generally had a chance to write a scientific article based on it. Several students remarked, however, that it would have been helpful to have more opportunity to consult with the instructors during the planning and data analysis stages of their experiments, a feature we will incorporate when the assignment is repeated.

Examples of Student Experiments

NiTi—a Shape-Memory Alloy

Several compounds described as shape-memory alloys exhibit the unusual property of "remembering" their shape when they are heated through a phase transition (*9, 10*). NiTi is a shape-memory alloy that undergoes a martensite–austenite phase transformation over a temperature range that can be customized by varying the alloy's composition.

Student-Proposed Experiments with NiTi

1. Weights were attached to a NiTi spring, which was suspended from a ring stand. When heated, the spring contracted owing to the phase change, and its length was measured as a function of attached weight.
2. A deformed piece of NiTi wire was placed in a thermostatic bath. The bath temperature was slowly raised and the transition temperature measured to ±0.5 °C.
3. Using a water bath accurate to ±0.1 °C, the time required for a deformed piece of NiTi wire to return to its original linear shape was measured as a function of temperature.

$Zr_{41.2}Be_{22.5}Ti_{13.8}Cu_{12.5}Ni_{10.0}$—an Amorphous Metal Alloy

A remarkable example of a customized material is the amorphous alloy Vitreloy ($Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10.0}Be_{22.5}$) (*11*). A kit containing samples of Vitreloy and stainless steel and a booklet describing these materials is available through the Institute for Chemical Education (ICE) (*12*). In the experimental setup, a stainless steel ball is dropped onto the surfaces of the two solids. The ball bearing bounces on the Vitreloy disk as if on a trampoline. The substantial difference between the ball's interaction with the stainless steel and with the amorphous metal surfaces is due to the different types of atoms and their arrangements on the two surfaces.

Student-Proposed Experiments with Amorphous Metal

1. The coefficient of restitution was measured for a stainless steel ball dropped onto the stainless steel and amorphous metal surfaces.[1]
2. The time from when the ball is dropped until it comes to rest was measured as a function of the initial height from which it was dropped.
3. Both of the aforementioned experiments were performed using balls of various sizes and materials.

Ferrofluid

Ferrofluids are colloidal suspensions of magnetic nanoparticles. The nanoparticles are suspended in either an aqueous- or an oil-based solution using a surfactant to prevent the particles from agglomerating (*13, 14*). A sufficiently strong and properly oriented magnetic field can cause spikes to form on the ferrofluid's surface.

Student-Proposed Experiments with Ferrofluid

1. By varying the magnet–ferrofluid separation, the effect on number and size of ferrofluid spikes was investigated.
2. The response of oil-based ferrofluid spikes to additions of acid, base, water, and salts was measured.
3. A student-designed glass apparatus was used to measure the change in buoyancy of ferrofluid when subjected to a magnetic field.[2]

Polydimethylsiloxane (PDMS) Polymer

PDMS is a transparent elastomer (*15*). The degree of cross-linking and thus the rigidity of the polymer can be controlled by varying the "base"-to-"curing agent" ratio when the polymer is prepared. Patterns such as optical transform arrays can be imprinted onto samples of PDMS.

Student-Proposed Experiments with PDMS

1. The rebound distances of four PDMS balls with different degrees of cross-linking were measured by rolling them down a flour- or talc-covered inclined plane and measuring the length of the rebound track left by the ball. This experiment was repeated with balls that were heated and cooled.
2. In a darkened room, a flexible PDMS optical transform slide was mounted on a ring stand with metal clips. Red and green pocket lasers were used to observe the effect of gently stretching the PDMS on the diffraction patterns, which were projected onto a wall several meters away.

Conclusion

Although this curricular experiment was carried out using examples from materials science, the methodology described could be coupled to many areas and levels of chemistry instruction at the discretion of the instructor. In the future, we anticipate using some of the same topics and adding new ones based on student suggestions and research breakthroughs. The key elements are the opportunity for students to create their own research problem, investigate it quantitatively, and communicate the results to technical and nontechnical audiences. Other variations that could be included to stress communication skills are poster sessions and oral reports.

Acknowledgments

We are grateful to the spring 2000 Chemistry 511 class, Writing Fellows Dave Jukam and Jane Peterson, and Bradley Hughes, Director of the UW–Madison Writing Laboratory, for their contributions to this paper. We also thank Betty

Emmons, Tom Ladell, and Ed Turner for help in securing lab space and equipment. This work was generously supported by the University of Wisconsin–Madison, Department of Chemistry, and by the National Science Foundation through the Materials Research Science and Engineering Center for Nanostructured Materials and Interfaces (DMR-9632527 and DMR-0079983) and GK-12/K-Through-Infinity Professional Development Partnership (9979628).

[W]Supplemental Material

Sample student reports are available in this issue of *JCE Online*.

Notes

1. The coefficient of restitution is defined as $(h_f/h_i)^{1/2}$, where h_i is the height from which the ball is released, and h_f is the initial rebound height. In the ideal case where the coefficient equals unity, the ball would rebound elastically to the initial height from which it is dropped.

2. The vertical displacement of a glass rod immersed in ferrofluid was measured a function of magnet–ferrofluid separation.

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