The Big Freeze: Water and the Scientific Process

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Abstract: In recent years there has been increasing movement toward laboratory exercises that are inquiry-based, requiring students to assume more active roles in the learning process. A laboratory experiment was developed in this light, framed around a simple question, "Which freezes faster, hot water or cold water?" The experiment was used at the beginning of the general chemistry year-long course sequence and served as an introduction to the scientific process. Students were each asked to develop a hypothesis and then design a simple experiment to determine which freezes faster, hot water or cold water, using small cold baths to freeze the water. A strength of this experiment is that students not only design and perform the experiments, but at the end they evaluate each other's methods.

Introduction

In recent years, there has been an increasing interest in creating laboratory exercises that are inquiry-based, requiring an investigative dimension on the part of the student [1–5]. Indeed, some schools have excelled in developing a "Discovery Curriculum" approach to their laboratories and lectures [6]. Such experiments more adequately represent the investigative nature of science and require students to assume more active roles in the learning process. Since experiments of this type are easily framed around a question or problem that is of broad interest and easily grasped by students, they can clearly understand and think about the objective of the experiment. Additionally, these experiments easily allow the scope of the investigation to be broadened for honors students, or narrowed for nonchemistry majors.

In this light, I wish to summarize a laboratory experiment developed for first-year college chemistry. At this level, inquiry-based experiments can really capture the imagination and interest of students, allowing them to experience what science and the scientific process are all about. This investigation was used as the first experiment in the fall semester of the general chemistry sequence, mostly as an introduction to the laboratory and the scientific process, but could easily fit elsewhere in a curriculum. One benefit to using this investigation at the beginning of the semester is that it does not require a lot of theory or laboratory skills. This experiment was repeated at the end of the second semester of first-year chemistry, allowing students to make experimental improvements and to incorporate principles learned in lecture.

The investigation outlined involves a seemingly simple question: "Which freezes faster, hot or cold water?" While it may seem that there is an obvious answer, the question stimulates heated debate, even among the scientific community [7]. While the question actually dates back to the time of Aristotle, who observed that "heating water actually contributes to the rapidity with which it freezes" [8], the recent history of the problem began in 1969 with an article published by Mpemba and Osborne [9]. Mpemba, a school boy in India, questioned a visiting university professor why, when making ice cream, warm milk freezes faster than room-temperature milk. Even today, upon polling students about their opinions, I found that roughly half of the students thought cold water would freeze first while the other half thought hot water would freeze faster. A few students thought there would be no difference in the freezing of hot or cold water. Indeed, upon testing my own hypothesis with samples of tap water at 22 °C and 72 °C, I found that the hot water consistently froze faster than the cold water.

One positive aspect to this investigation is that the question to be examined is readily understood by the students. Exceptionally prepared students are not bored, less-prepared students and chemistry neophytes are not put off. This is especially important at the beginning of the fall semester when faculty must struggle to provide meaningful laboratory experiences to a body of students with varying high-school chemistry backgrounds. Given that the first few weeks of the semester are often spent discussing basic aspects of chemistry such as matter, measurements, and the foundations of atoms and molecules, it is difficult to program experiments during the first few weeks of lab that the students perceive as interesting and that ignite a spark of interest in the students, setting the tone for the rest of the semester.

The main crux of this experiment is that it allows students to design their own experimental procedures. Although it is expected that few students will have the background to design elaborate experimental protocols, they do have enough basic knowledge to design a simple experiment. Additionally, it is very interesting to observe what the students come up with. This allows the professor to gain some insight about the relative ability, curiosity, motivation, analytical-thinking skills, and depth of thought each student brings to college.

Laboratory Exercises

The student handout (included in the supporting information 530133abs1.zip) discusses the basics of the scientific process and asks a student to hypothesize which water will freeze faster and then to devise a short experiment to test this hypothesis. Students are encouraged to be creative in their designs but a few guidelines are included, for example, that smaller volumes of water in test tubes will be easier to freeze than larger volumes in beakers. Students are also told how to construct a –10 °C cold bath using ethylene glycol and dry ice. If dry ice is not readily available, suitable cold baths can be made using mixtures of ice, water, and various salts such as NH_4Cl [10]. If the bath can be easily maintained at –10 °C, it will work well. The use of the cold bath causes the water samples to freeze much faster than if a traditional freezer were used, makes it easier to monitor the freezing of the water samples, and alleviates problems that would be encountered by students opening the freezer every few minutes to add new samples or to check on the progress of samples in the freezer. Most samples were frozen within 20 minutes (many within 10 min). All students performed at least two trials to demonstrate the consistency of their results. As their prelaboratory assignment, students submitted brief outlines of their experimental procedures along with a list of the supplies needed. These were then reviewed before the laboratory session to ensure that they were reasonable and that the necessary supplies were available.

Students were not told what was meant by “hot water” or “cold water,” and were encouraged to avoid changing their experimental procedures simply because another did something different. They were encouraged to follow their own scientific instincts. The intent of the first run of this experiment was not to have the class get a unified set of results, but rather to demonstrate more fully the scientific process and the importance of experimental design and attention to detail in the laboratory. Rarely do our first attempts at experimental design give us the desired results.

Supplies. The following items are needed for this experiment.

- dry ice
- ethylene glycol (or another suitable cold bath combination such as NH_4Cl–ice)
- 2–3 test tubes per student or group
- a stopwatch
- test tube clamps
- hot and cold water
- a small vacuum-insulated container or polystyrene foam cup to be used as the cold bath.

Results and Discussion

As anticipated, the experimental designs were extremely varied. Some students had obviously put a lot of thought into their designs, while others significantly less. Distilled, tap, and boiled water were used and there was quite a wide variation in the temperature of the “hot” and “cold” water used. Most students used test tubes filled with water. Some students carried out the hot and cold water runs in tandem while others froze both the hot and cold water samples at the same time in the cold bath. Some students stirred their water samples as they froze while others simply let them stand. Regardless of the experimental design, all students were easily able to complete multiple runs during the laboratory period (3 hours).

Approximately half of the students found that their experimental results proved their hypotheses correct, while the other half were perplexed that the experiments did not confirm their hypotheses. There was no correlation between the hypotheses the students initially made and the results. Some students who thought cold water would freeze faster found that hot water froze faster, and some who thought hot water would freeze faster found that cold water froze faster.

As the students finished their experiments, they created a table in their laboratory notebooks with other student data; a similar table was created on the classroom chalkboard. Typical results from each laboratory section showed that about half of the students found that cold water froze faster and half found that hot water froze faster. The students were then placed in small groups and asked to discuss both their individual results and how as a group they got different results while performing what seemed to be the same experiment.

The students were quite adept at discovering differences in how they executed their own experiments. Soon many experimental variables were elucidated, including whether students used matching test tubes, what type of water was used, whether the hot and cold samples were run at the same time or in tandem, whether the water samples were completely submerged in the cooling bath, and even the determination of “freezing.” Other students (the ones with better backgrounds) speculated about dissolved gases or salts affecting the freezing point of water. In all, students did good jobs assessing the strengths and weaknesses of their own experiments. They were asked to state in their laboratory reports how they would change their experiments to improve them to (hopefully) give more reliable results

Although some students were put off by the lack of cookbook-style instructions, most enjoyed this experiment and the discovery-based approach it involved. Indeed, much debate was generated by some of the students about the results of their inquiries. In this light, the experiment was repeated as the last laboratory at the end of the first-year general chemistry course. As students then designed new and improved experiments to test their hypotheses, they were encouraged to integrate not only the weaknesses of their earlier experiments but also what they had learned during the intervening two semesters of general chemistry.

As expected, experimental designs of the second attempts were much better, with greater attention paid to the many variables that plagued earlier attempts. Most students used distilled water heated to boiling (to remove gases) and then cooled to use as the cold sample. When polled before beginning, most students were convinced that the cold water should, and would, freeze faster. A few students clung to their beliefs, based upon their earlier experimental results, that hot water would freeze faster. As the students concluded their experiments, results were again tabulated on the board. To their amazement, the experimental results matched their predicted hypotheses and 90% of the students had observed that cold water froze faster.

Although one might naively state that all the students did was design experiments that proved cold water would freeze faster under the right conditions, that assumption fails to recognize several important aspects. First, in order to design better experiments, students must incorporate what they learned from their earlier experimental attempts and what they learned during the year. Students need to realize that scientific knowledge is a tool that can be used to help understand new problems and that “failed experiments” or ambiguous results, when analyzed in a thoughtful way, can often provide knowledge useful later.

Second, many students made connections between this experiment and other aspects of chemistry that might not seem related to the question posed. For example, some students became interested in using computer-controlled temperature probes to monitor the changing water temperature over time. While cooling rates may not directly answer the question posed, they are interesting connections which could constitute a study by themselves. Other students thought that by using computer-controlled temperature probes that plotted the cooling curves as the experiment progressed, it would be easier to determine when the water was frozen because the temperature would no longer be "flat-lined" at the freezing point, but would begin to drop below the freezing point. That students would attempt to make these types of connections *on their own* at an early stage in their scientific training is very valuable; this certainly needs to be encouraged.

In conclusion, the experiment was successful in many ways. Students enjoyed it and became *actively engaged* in the laboratory. The experiment was not only fun to do, but perhaps more importantly, students were really interested in the outcome of their experiments. For many students, this experiment served as a springboard for discussions not only with laboratory peers and professors, but also with friends and families. Chemistry was alive and relevant, and students began to develop critical-thinking skills that allowed them to make connections between chemistry and the world around them.

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References and Notes

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