Second-Year and AP Chemistry

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Authentic Research within the Grasp of High School Students

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It is very difficult for students to understand how research is done. We seldom provide them with the opportunity to answer questions that have not been thoroughly discussed in their textbooks. Too often they merely follow step-by-step procedures designed to confirm well-established theories.

The need to provide authentic research experiences for students is one of the goals of the *National Science Education Standards*, which state that "Learning science is something students do, not something that is done to them" (*1*). It is further stated (teaching standard D) that

> Teachers of science design and manage learning environments that provide students with the time, space, and resources needed for learning science. In doing this, teachers
>
> > Structure the time available so that students are able to engage in extended investigations.
> >
> > Create a setting for student work that is flexible and supportive of science inquiry.

and (teaching standard E) that

> Teachers of science develop communities of science learners that reflect the intellectual rigor of scientific inquiry and the attitudes and social values conducive to science learning. In doing this teachers
>
> > Nurture collaboration among students.
> >
> > Structure and facilitate ongoing formal and informal discussion based on a shared understanding of rules of scientific discourse.
> >
> > Model and emphasize skills, attitudes, and values of scientific inquiry.

One fall a colleague proposed a problem that provided a perfect opportunity for real research. Will an ice cube melt faster in salt water or tap water? Most people will probably predict that it will melt faster in salt water because they are thinking about the use of salt to melt sidewalk ice. In fact when I asked a class of 26 ninth-grade students to predict, there were 20 who predicted it would melt faster in salt water and 6 who predicted tap water. When asked the reason for their prediction 18 students cited the use of salt to melt ice on roads, and even two of the students who predicted tap water mentioned of the use of salt on roads. My AP chemistry students made similar predictions.

I asked students to list all the variables that might affect the rate of melting and found that all of them were able to list at least 3 different variables: size of ice cube, amount of water in cups, and temperature of the water. In group discussion a much longer list of variables was generated. The list included shape of ice cube or surface area, amount of salt added to the water, the room temperature, type of container that the water is in (beaker vs Styrofoam cup), movement of water or any agitation of water, size of beaker used, and radiant light falling on beakers.

The students did not have any trouble understanding that to test which ice cube melts faster they would have to keep everything the same except the salt. I didn't bother having them do this part of the experiment because of time constraints. A possible variation would be to have the students test the rate of melting of ice in tap and salt water at home and then discuss their observations the next day in class. Instead I told them that when a friend had asked me which should melt faster; I wasn't able to answer the question with any certainty. I then described the results of my experiment.

I made two ice cubes of exactly the same size. In the first trial I placed 100 mL of salt water in one Styrofoam cup and 100 mL of tap water in an identical cup. Both cups were at the same initial temperature. I found that the ice cube took about 12 minutes to melt in tap water and there was still a sliver of ice remaining in the salt water cup after 48 minutes. This was totally unexpected but poses the interesting question why? There followed a discussion about how we should repeat this experiment to see if every time the ice cube in salt water melts slower. But I told them that several other people and I had repeated the experiment multiple times and always found that the ice cube in salt water melted slower.

When I tested this, I used 16 grams of salt per 100 mL of water and I made all my ice cubes by pouring 20 mL of water into small Solo cups with lids (plastic souffles no. P200 2-oz size with lid PL2). The advantage of using the Solo containers is that it is easy to stack many of these in the freezer and make identical ice cubes.

The real challenge is to come up with an explanation for why this should happen. The answer is not immediately obvious. I told them that I had asked a number of teachers and even a Ph.D. chemist and that no one had a ready answer, but that everyone was intrigued by the problem. We have an opportunity to do what real scientists do—figure out a model to explain the behavior observed. Students were told to write down what they thought might be happening. Since scientists don't work in isolation we need to discuss our ideas. Brainstorming possible reasons is the next step. Students were told to discuss in small groups what might be happening and if possible to think about how they might test their different theories.

After allowing the students time to discuss their ideas, I asked students to volunteer possible explanations. When a model was proposed to explain why ice would melt slower in salt water, I encouraged students to think about an experiment that could be done to test it. Since they were studying atomic theory, I pointed out that Rutherford's experiment was not to prove that the atom had a nucleus but was designed to test J. J. Thompson's "plum pudding" model. The results of the gold foil experiment were totally unexpected because Thomson's model would have predicted that the α particles would pass through undeflected. Rutherford had to propose a new model that would fit with his experimental evidence.

What we need to do is come up with some possible models that we can test experimentally. If we propose a model that cannot be tested, then we can never prove or disprove it.

Possible Explanations

1. Several students suggested that the ice cube is floating higher in the salt water and heat is not transferred as efficiently between the ice and air as between the ice and water. They decided to hold both ice cubes below the surface of the water and see if the difference in melting time would disappear.
2. Some students proposed that salt water did not transfer heat as easily as tap water and decided to measure the temperature vs time for melting an ice cube in salt and tap water.
3. One student proposed that there was something about salt that accounted for this behavior and decided to see if a sugar solution produced the same results.
4. One student who predicted that it would melt faster in tap water wrote "because the salt may insulate the ice to keep it colder, longer." I asked him to expand on that and asked if he meant that the water around the ice would move more slowly. When he agreed, I suggested that perhaps looking at a colored ice cube would test this.

Interestingly, the AP chemistry students proposed many more complicated explanations for the difference in melting time. They tended to focus on ionic bonding and the polarity of the water. They tried to create complex models for the interaction of the salt ions and the water molecules and they initially had some difficulty in designing simple tests for their models. However, with minimal help from the teacher they were quickly able to decide on simple initial tests.

We ended day one with our discussion of possible models and tests that we might do. The students were told that the next day I would provide them with lots of ice cubes of identical size and shape, tap water and salt water of the same temperature, and an assortment of thermometers, metal washers for sinking the ice cubes, sugar, and additional salt. I decided to add red food coloring to all the ice cubes because it would make it easier for students of observe the mixing of the melted ice and the water. Neither group of students questioned the addition of the food coloring, but I was prepared to tell them that since one of the groups had decided to use colored ice cubes it was just easier to add the food coloring to all of them. I had a few noncolored ice cubes available if any group thought that the food coloring would affect their results.

On day two we briefly reviewed the various models that we had proposed on day one. Students were told that they could test any of the theories or models that they thought were promising. Since scientists work in various-sized groups, the students were told they could work by themselves or work in larger groups. Several students elected to work alone and only one group of five formed. Scientists share their research, so the students were encouraged to observe other groups' experiments as well as their own. We made a table on the board to organize our theories (Table 1).

Before beginning their experiment students were asked to write out exactly what procedure they would follow.

Observations

I have used a table to summarize the students' observations and I have also slightly reworded their original explanations because as they discussed the problem they clarified their thinking (Table 2).

Several students decided that the density difference between salt water and tap water could explain the observations. I encouraged them to share their theory with other students.

Experimental Conclusions

When the class reconvened we compared our observations with the four models that were initially proposed. We then took the evidence and eliminated models 1 and 3. Several students explained the convection currents observed as cold denser water sinking into the tap water and they were able to explain the melted ice water rising in salt water because it is less dense than the salt water. Students realized that if the cold water was sinking in the tap water but remained floating in the salt water, their temperature measurements in test 2 were easily explained. We revised the fourth theory to explain the difference in melting times in terms of the melted ice water forming an insulating layer around the ice cube in salt water because of the density difference between salt water and the melted ice. This melted ice water layer prevented mixing and kept the ice cube away from the warmer salt water. Since the room-temperature tap water was less dense than the melted ice, the cold ice water sank in tap water, causing mixing; the ice cube was continually touching the warmer tap water, so it would melt faster. We looked at the results of all our experiments and decided that they all fit with our revised version of the fourth theory.

Are we done? Scientists create models to explain observed behavior and they use the models to make predictions. If the predictions do not match the model then a new model is

Table 1. Students' Table Organizing Their Theories

Possible Explanation or Proposed Theory	Test	Prediction from Proposed Theory
1. Ice is floating higher in salt water so it does not lose heat as efficiently as it would if more ice was in contact with water.	Sink the ice.	Ice cubes in salt water and tap water will melt at the same rate.
2. Salt water does not transfer heat as efficiently as tap water.	Measure temperature of salt water and tap water as ice melts.	Salt water temperature should not decrease as much as that of tap water.
3. There is some property of salt that accounts for the unique behavior.	Compare the rate of melting of ice in salt water, sugar water, and tap water.	The rate of melting in sugar water will be the same as tap water.
4. There is less mixing of the melted ice water in the salt water.	Use a colored ice cube.	The food coloring from the colored ice will be concentrated around the ice cube in salt water but not in tap water.

Table 2. Summary of Students' Theories and Observations

Possible Explanation	Tests	Prediction	Observations	Does It Match Prediction?
1. Ice in contact with water melts faster because heat transfer is more efficient between ice and water than ice and air.	Sink ice	Ice cubes in salt and tap water will melt at same rate.	1. "Wavy lines" rose from the cube as it melted in salt water. If a colored ice cube was used, the food coloring mixed quickly throughout the salt water. (Fig. 1.) 2. Food coloring formed a layer on the bottom of the beaker when ice submerged in tap water. (Fig. 2.) 3. Submerged ice melted faster in salt water.	No
2. Salt water has a higher specific heat that tap water.	Measure temperature of salt water and tap water as ice melts.	Salt water temperature should not decrease as much as tap water.	Temperature of the salt water did not change as quickly as the tap water.	Yes
3. The ionic nature of salt is responsible for the observation.	Compare rate of melting in salt water, sugar water and tap water.	Rate of melting will be the same in sugar water as tap water.	1. Ice melted slower in sugar water than in tap water. 2. Rate of melting was inversely proportional to amount of salt or sugar dissolved in water	No
4. Melted ice water does not mix with the salt water as readily as with tap water.	Use colored ice cube	Food coloring will be concentrated around the ice cube in the salt water but not in the tap water.	1. Small streamers of red food coloring could be observed moving downward from the ice cube as it floated in tap water; the tap water quickly became red throughout. (Fig. 3.) 2. A layer of food coloring appeared on top when the ice melted as it floated in salt water. (Fig. 4.)	Yes

needed. Models are constantly tested, though, so one test is not enough. It looks as if the difference in melting time for an ice cube in tap and salt water is due to the lack of convection currents. I asked the students if there was another test we could do to see if the difference in rate of melting was simply due to lack of mixing. A student suggested that if we stirred the ice cubes in water that there should be no difference in the rate of melting. We took two beakers with identical volumes of tap water and salt water and the same initial temperature and added the ice to each as one of the students stirred them simultaneously with two thermometers. We found they both melted within two minutes and that the final temperature of each cup was the same after melting. Not only did our new model predict the result but it also showed that the salt water and tap water had no noticeable difference in their specific heats, eliminating theory two decisively. Did we prove our theory? If another experiment does not fit our model then we will have to revise our model, but we have managed to propose a model that fits all the experimental data. I also believe that the students have a much better idea how scientists develop and test theories as a result of doing this exercise.

Extensions

Models are not much good if they don't have real-world applications. Where else do we see this? Have you ever noticed the watery layer around ice cubes left undisturbed in a cup

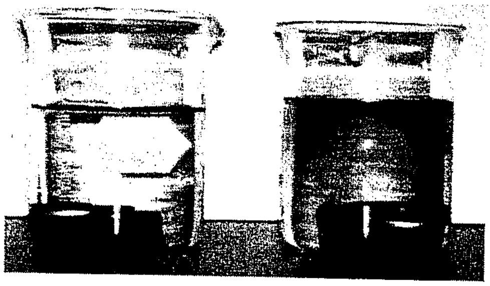

Figure 1. Note that "wavy lines" or plumes of food coloring rise from the ice cube submerged in salt water.

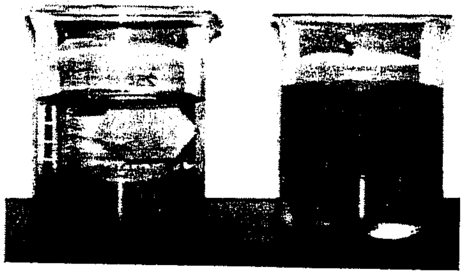

Figure 2. The food coloring from the melted ice has mixed throughout the salt-water beaker but forms a layer on the bottom of the tap-water beaker.

Figure 3. Note "wavy lines" or plumes of red food coloring are observed to sink as the ice cube melts in tap water. The ice cube in salt water does not appear to mix with the salt water as it melts.

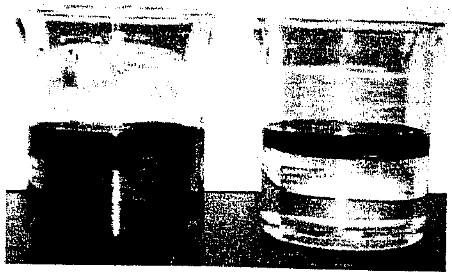

Figure 4. Food coloring is mixed throughout the tap water after the ice cube melts. In the salt water the food coloring from the melted ice cube floats above the salt water.

of cola? What other examples have you seen? The book *Convection, a Current Event,* in the Great Explorations in Math and Science series, has some wonderful activities that can be used to study the movement of liquids and gases due to density differences (*2*). Convection is one of the ways by which heat moves in a fluid. The fluid can be any substance that flows: water, magma in the earth, or gases such as air. Without convection there would be no wind, no ocean currents, no mountains. Uneven heating of the atmosphere produces huge convection currents that span thousands of miles, creating the major wind patterns on the planet. These global convection currents are responsible for monsoons, the trade winds, and the doldrums. Meteorologists take both global and local convection currents into account in predicting weather patterns.

Summary

Exercises like this clearly match the National Science Standards for teaching and are much more interesting than standard laboratory exercises. When asked if they thought this investigation was worthwhile, the student response was an overwhelming—yes! As one student put it, "We got to think about a real problem and try to solve it. It's a lot better than what we usually do." I have been unable to find many other examples of similar investigations in the literature, but I wish to acknowledge reading and using a similar problem described in this *Journal* on why gold rubbed on the face of some people leaves a mark, but on others does not (*3*). I have used this question for many years as a way to introduce the scientific method and have found it, like the problem discussed in this article, a rich vehicle for discussion of experimental design.

Literature Cited

1. *National Science Education Standards*; National Academy Press: Washington, DC, 1996; p 20.
2. Gould, A. *Convection, a Current Event*; Lawrence Hall of Science, University of California: Berkeley, 1988.
3. Mattson, W. *J. Chem. Educ.* 1988, *65*, 1000.

A Simple Demonstration for Introducing the Metric System to Introductory Chemistry Classes

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The following is a simple exercise that can be used to demonstrate the concepts of SI units, experimental design, and significant digits in a manner that holds the attention of students who already understand these concepts but is still instructive for students who are less well prepared. An advantage of this demonstration is that it takes material that is too easily treated in an abstract manner and turns it into a concept students can visually interpret.

Linear measurement (length) is a very simple and easily understood concept. Students are already familiar with several different units of length, such as inches, feet, and miles. A short discussion on when use of each of these is most appropriate should illustrate why different standards are useful. For example, students can be asked how tall they are in miles or how many inches are driven in the Indianapolis 500. While students obviously know the definitions of most familiar units of length in terms of each other (e.g., 12 inches = 1 foot), most of them will probably not be as comfortable with the concept that all these units are based on some rather arbitrary standard. This is an important point, but the previous illustrations show that none of the commonly used units are intrinsically any better than any other unit.

To demonstrate how a system of measurement can be generated, the width of the lecture hall can be defined as a "room". Choice of this standard as a base unit instead of a more conventional length (such as a meter or a foot) is designed to place all students on a more equal footing. Solicit volunteers to unroll a paper streamer the width of the lecture hall and cut it to prepare a length one room long. Discuss the fact that while this unit of measurement is convenient for some distances, it is too long for measuring smaller lengths. Have a volunteer hold each end of the streamer and have nine additional volunteers place themselves so they can mark ten approximately equal segments. Once everyone is satisfied that they are spread as evenly apart as possible, cut the streamer into ten pieces and tape one of these pieces to the front wall in clear view of all students. This unit is defined as a deciroom and is equal to $^1\!/_{10}$ of a room. The emphasis at this point is on the fact that the SI prefix deci means $^1\!/_{10}$. A suggestion to add a little fun to the required memorization of these prefixes has been made (*1*).

Have several pairs of students hold up some of the deciroom pieces, which will illustrate that these pieces are not all the same length. Give the students an opportunity to come up with a better method for dividing these pieces into ten equal lengths. Typically, most students have already figured out that folding into ten pieces should be much more accurate. This provides an obvious opportunity to discuss the importance of carefully designing experiments and it can be used to introduce discussion about the laboratory portion of the course. Next, have students take one of the deciroom pieces, divide it into ten centiroom lengths, and compare the length of these pieces. Tape one of these centiroom pieces below the deciroom length. Seeing the different lengths displayed gives students a physical picture of how much an order of magnitude changes a measurement. If desired, one of the centiroom pieces can be given to a volunteer to make ten milliroom lengths.