Developing Teachers’ Understanding of the Nature of Scientific Inquiry with Embedded Data Collection Materials

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Abstract: Middle and high school science teachers generally do not hold an inquiry-oriented view of school science. This may be ascribed to the interaction of two factors: (1) teachers’ limited understanding of the nature of scientific inquiry itself, and (2) content-oriented curricula, with a focus on verification labs and discrete, guided discovery experiences. In order to impact these impediments to change, we have incorporated real scientific inquiries into our teacher education program. These inquiries involve beginning teachers in using a programmable data collection device to answer seemingly simple questions of personal interest. The resulting “messiness” of the real data collected provides genuine insight into the nature of scientific inquiry and the necessity of its incorporation in classrooms.

Introduction

For at least thirty years, science teacher educators have attempted to encourage beginning teachers to adopt a more inquiry-oriented view of school science, but these attempts have only been partially successful. Inquiry is central to scientific practice, yet in today’s middle and high schools, even when students perform experiments, it is usually with a closed set of materials that have been provided to them, with all of the potential variables so tightly controlled there is little to do but replay a mechanical procedure.

Our work focuses on supporting beginning teachers (both pre-service and those in their first three years of teaching) to develop a better understanding of the nature of scientific inquiry. Even having received undergraduate (and sometimes graduate) degrees in science, it is our contention that those new to the teaching profession cannot envision what scientific inquiry might look like in classrooms. They remain wedded to the verification lab activities experienced in their own education. Consequently, we involve graduate students (enrolled in a M.Ed. and teacher licensure program) in designing, debugging, and carrying out their own science-based inquiries.

Beginning teachers in our program are encouraged to think about questions of their own and use project technology (data collection with handheld, programmable devices) to help them explore their questions. Our work in this area shows great promise. Beginning teachers have gathered data to explore the efficacy of wet-suits, studied an attic’s insulation performance after a home improvement project, and determined which family member takes the hottest baths. It is the personal connection to the questions and their exploration prior to hypothesis formation that students in classrooms fail to experience—what we refer to as “the front end of scientific work.” This paper provides a documentary account of our work to date, as we conduct research that asks:

What uses of embedded, computational tools enhance teachers’ awareness of the nature of scientific inquiry and in particular the “messiness” of collected data? How do they anticipate, respond to, and account for unexpected data?
Theoretical Framework

Any biography of a well-known scientist reveals that scientists are deeply connected to the questions and ideas they are studying, often to the point of obsession. Scientists take a problem or question and make it their own (Derry, 1999). National professional societies (Rutherford and Ahlgren, 1989; National Research Council, 1996) have pointed to the pivotal role scientific inquiry should play in school science as a means of assisting students to understand “what science is, what science is not, what science can and cannot do, and how science contributes to culture” (NRC, 1996, p. 21). Yet teachers rarely provide opportunities for students to experience scientific knowledge in this way. To the contrary, scientific knowledge is presented as a fait accompli, already discovered and fully researched by the great minds of the past.

Historically, high school science laboratories were assumed to provide students with inquiry-based experiences (Spears & Zollman, 1977), but modern definitions of inquiry allow us to better interpret student work in the laboratory environment and its impact on science learning and students’ conceptions of the nature of science. In many cases, science labs are a contrived experience in which students follow recorded procedures to obtain results that are already known (McComas, 1997). While these labs may help students develop basic process skills, they do little to allow students to pursue creative problem-solving, and encourage a portrayal of science as facts that are revealed only when the prescribed scientific method is followed (Pizzini et al., 1991).

Lederman’s (1998) extensive work on scientific inquiry (SI) and the nature of science (NOS) has indicated how science teaching needs to change to address modern views of these central ideas. While observing that the meaning of the “nature of science” has been in flux over decades of thought, Lederman defines it to include the principles that science: is subject to change, is based on observations of the natural world, and involves creativity as scientists draw inferences from the data collected. Lederman contends that our contemporary views of SI and NOS should be taught, not simply left to emerge from any particular set of classroom activities: “If K-12 students are expected to develop more adequate conceptions of the NOS and scientific inquiry, then, as any cognitive objective, this outcome should be planned for, explicitly taught, and assessed” (Lederman, 1998).

If teachers themselves have little experience with scientific inquiry, or even if they do, they may be unable to incorporate it in their classroom work, or may proceed under the mistaken impression that students will gain the necessary understanding of NOS and SI from the prescriptive labs that are the norm of high school science. This line of reasoning has led us to engage beginning teachers in the types of projects that become an authentic inquiry. We have encouraging beginning teachers to “think outside of the box”— that is, during the course of their M.Ed. program, conceive of and carry out a project other than demonstrating a scientific principle with which they are already familiar.

Methodology

This paper is based on work conducted over three consecutive offerings of a graduate-level course, “Science for Science Teachers.” This is a required course in our M.Ed. program in Curriculum and Instruction with Science specialization. It is offered during our summer session and enrolls about 20 students. Most students are practicing teachers, but about 20% are pre-service. In this paper, these students of our course are referred to as “teachers,” to more easily distinguish this work from research involving PK–12 students.

The course is an introduction to the history, nature, and philosophy on science, with a focus on putting this understanding to work in the classroom. Teachers read national standards documents, literature on the nature of science, and complete a historical research project on a famous scientist. There is also a project module, which runs through the length of the course. The basis for the project involves
teachers conducting an experiment that allows them to form a hypothesis about some phenomenon in the world. Their experiment is not supposed to result in a complete explanation of the phenomenon, but rather give them the foundation for building a hypothesis around its explanation.

Beginning in the summer 2002 course offering, we introduced the Handy Cricket microcontroller (Figure 1). The Handy Cricket is a small, inexpensive embeddable, programmable device that is popularly used for classroom and hobbyist robotics projects (Martin et al., 2000). It has been used in the past for students and teachers to develop scientific experiments (Resnick et al., 2000).

In the new project module, teachers were given kits that included the Handy Cricket, sensors, and the necessary software to use the Cricket at home. In the first two offerings of the course, each group was given just one light sensor and one temperature sensor. In third offering, we provided a more extensive kit that included motors and lamps, but we still focused on the light and temperature sensors. One in-class session was dedicated to showing teachers how to use the Cricket. This instruction focused on showing teachers how to conduct data-collection experiments using the Cricket. Teachers learned how to program their Cricket to collect and store either one or two data series, with an adjustable interval between each data sample. They were shown how to upload the data into a comma-separated text file, and import that file into a spreadsheet program for viewing and graphing. Then, teachers brought the materials home, and conducted their own experiment using their own PCs or borrowed laptops.

As mentioned, teachers were expected to pursue some kind of investigation that gave them the basis for formulating a hypothesis about a phenomenon in the world. They were not expected to develop an investigation to the level where they could make a substantiated claim, but rather to develop a “testable question.” For each run of the course, the teachers’ work took place over the course of approximately one month. They were required to collect at least two data sets (the better projects involved more data collection than this), prepare and lead an in-class presentation, and turn in a written report.

**Results and Discussion**

Table 1 summarizes teachers’ projects over the 3 iterations of the course. The 27 total projects are grouped into 7 content areas: Home Heating and Cooling, Car Heating, Clothing and Personal Wear, Beverage Quality and Safety, Nature and Environment, Human Perception, and Understanding Systems. These areas have emerged from a post-analysis of the teachers’ work; they were not discussed with teachers during the course of the work. The assignment produced a surprising range—far more than we anticipated, especially given the limited sensor set with which teachers were provided (light sensors and temperature sensors). To us, this reflected the enthusiasm that many of the teachers brought to their projects, and the “malleability” of our materials.
In addition to the range of content, we noted a number of common themes that connect directly to teachers’ experience of the nature of science. These themes are now discussed with examples drawn from the teacher projects.
Table 1: Summary of 27 Teacher Projects

<table>
<thead>
<tr>
<th>Content Areas</th>
<th>Project Details</th>
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<tbody>
<tr>
<td><strong>Home Heating and Cooling</strong></td>
<td>• is my insulated attic warmer than non-insulated garage?</td>
</tr>
<tr>
<td>(6 projects)</td>
<td>• is my bedroom cooler than my roommates”?</td>
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<td></td>
<td>• does doing the laundry heat up my basement?</td>
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<tr>
<td></td>
<td>• do parts of my home warm differently in summer?</td>
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<tr>
<td></td>
<td>• does it work to draw shades during day to stay cool?</td>
</tr>
<tr>
<td><strong>Car Heating</strong></td>
<td>• does car color make difference in heating from sun?</td>
</tr>
<tr>
<td>(2 projects)</td>
<td>• how fast does car heat with windows open vs. closed?</td>
</tr>
<tr>
<td><strong>Clothing &amp; Personal Wear</strong></td>
<td>• do my 3 types of wetsuits actually perform differently?</td>
</tr>
<tr>
<td>(3 projects)</td>
<td>• what color T-shirt is best to stay cool in summer?</td>
</tr>
<tr>
<td></td>
<td>• do polarized sunglasses work better than non-polarized?</td>
</tr>
<tr>
<td><strong>Beverage Quality &amp; Safety</strong></td>
<td>• what container is best to keep my coffee hot?</td>
</tr>
<tr>
<td>(3 projects)</td>
<td>• does my milk delivered in summer stay cold all day?</td>
</tr>
<tr>
<td></td>
<td>• what sort of wine cooler works best?</td>
</tr>
<tr>
<td><strong>Nature &amp; Environment</strong></td>
<td>• what location around home gets best sun for garden?</td>
</tr>
<tr>
<td>(5 projects)</td>
<td>• which window in my home gets best sun for plants?</td>
</tr>
<tr>
<td></td>
<td>• what is relationship between light and temperature in a forest? (2 projects)</td>
</tr>
<tr>
<td></td>
<td>• what is relationship between light and temperature in swimming pool?</td>
</tr>
<tr>
<td><strong>Human Perception</strong></td>
<td>• does my heating pad continue to heat my back, or stop working?</td>
</tr>
<tr>
<td>(3 projects)</td>
<td>• why does my soda sometimes seem really cold and other times not?</td>
</tr>
<tr>
<td></td>
<td>• which person in my family takes the hottest bath?</td>
</tr>
<tr>
<td><strong>Understanding Systems</strong></td>
<td>• can I build system to demo evaporative cooling? (2)</td>
</tr>
<tr>
<td>(5 projects)</td>
<td>• does wood deck heat more than patio brick in sun?</td>
</tr>
<tr>
<td></td>
<td>• do sunflowers actually track sun’s motion over a day?</td>
</tr>
<tr>
<td></td>
<td>• how does cold air distribute itself inside a refrigerator?</td>
</tr>
</tbody>
</table>

**Understanding and Trusting the Data**

Ultimately, each of the projects centered on data sets that the teachers had collected, and the narrative that they developed around them. The key task for each teacher was to interpret the data in a way that was plausibly consistent with reality—first convincing oneself of the validity of the explanation, and then presenting it to others.

Figure 2 is a typical example. It shows data from a teacher’s investigation of the question, “will chilling agents (a frosted glass or ice cubes) keep refrigerated water colder, over the course of a typical drinking time, than the refrigerated water without a chilling agent?” In the graph, the horizontal axis is the sample number, corresponding to elapsed time, and the vertical axis is a heat reading, which is inversely proportional to temperature. (Why temperature is inverted will be discussed later). Run 007C used just chilled water. Run 008FG used chilled water and a frosted glass, and Run 009IC used chilled water and an ice cube. The data appear to show that plain chilled water gradually warms, chilled water in the frosted glass rapidly cools and then warms, and the water with ice cubes more slowly cools and then warms.

This sense-making from the raw data was often a complex process. The Figure 2 data were obtained only after an earlier run, in which the water with ice cubes showed a sharp cooling spike. The teacher-experimenter postulated that ice cubes were directly striking the sensor, so she built a wire-mesh apparatus to protect the sensors from direct ice cube contact (see Figure 3) and re-ran her experiments, then obtaining the Figure 2 data.

In another project, a teacher was trying to determine how the use of the washing machine affected basement temperature. In one of her experimental runs, the Cricket recorded exactly the same temperature in a few hundred samples over an 8-hour period. She wasn’t sure if this was indeed the case or an equipment malfunction. Because the washing machine had not been used that day, and neither she nor her
children had gone down to the basement during the sample period, she decided the data were correct. In this and other instances, the matching of experimental measurement to physical reality was complex.

Adapting and Customizing the Instrumentation

In many of the projects, adaptations were necessary to use the Cricket and its sensors in the intended application. Figure 3 shows two examples of this. On the left, a Cricket is mounted on a wooden block with its light sensor and temperature sensor held in a fixed relationship. Two copies of this apparatus were made; the teachers who designed the mounting fixture were concerned that the both Cricket-blocks measured the temperature-light relationship in the same way. The picture on the right shows Cricket temperature sensors protected with a wire screen mesh; as mentioned, the modification arose after a teacher noticed unusual spikes in her data of liquid cooled by ice cubes. After adding the wire mesh, the spikes disappeared. Other similar work (not pictured) was done by teachers who were measuring sunlight levels; the light sensors easily saturated, and in several projects, teachers developed various forms of shielding to allow the light sensor to generate a full range of values over the course of light variations from dawn to dusk.

Calibrating Sensors

The sensors we gave to the teachers reported their data along a scale that was correlated to electrical voltage rather than to standard units. Sensors reported values between 0 and 255 (inclusive). The light sensor reported higher values in darkness, and the temperature sensor reported higher values in
colder temperatures. This issue caused some consternation among the teachers, particularly for the temperature sensor, where the scale not only did not correlate with familiar ones, but was also inverted. Many of the teachers, though, learned to think in “Cricket Units” over the course of their projects. In their final reports and classroom presentations, they displayed graphs of sensor data where the vertical axis was raw Cricket units, and we noted from the classroom discussion that the class as a whole was comfortable thinking about the data in these terms.

Several of the projects, on the other hand, necessitated some sort of calibration of the sensors. There were two sorts of calibration that we noted: (1) calibrating sensors to each other—in other words, determining that two temperature sensors reported the same value at the same temperature, and (2) calibration of Cricket units to a standard scale (e.g., Fahrenheit). This issue arose particularly in the third year of work, in which we made more equipment available to the teachers (so they had two sensors of the same type). In several of the projects that involved environmental temperature measurement, teachers relied on internet sources of local temperature, and therefore needed to convert their Cricket measurements to standard units. These teachers developed sub-experiments to correlate their Cricket readings to the standard units.

**Personal Connections**

The teachers often chose to explore a question or phenomenon that was of close personal interest. For example, one teacher had recently completed a home improvement project in which she insulated the attic of her house. She was curious as to its heat retention properties, and developed an experiment to compare it to the attic of her garage, which was similar in construction but was not insulated. Another teacher who was a diving enthusiast designed an experiment to compare the heat retention performance of several different models of wet suits that he owned. Others attempted to resolve household disputes, such as whose room is the coolest and who takes the hottest bath. One teacher’s family received old-fashioned milk deliveries, and she was curious if her method of keeping the milk cold while it was still outside during a summer day was adequate.

**Studying Human Perception**

An intriguing area of study involved studying one’s own perceptual experiences. The highlight of these experiments was conducted by a teacher who regularly used a heating pad on his back. After he had the pad on for a while, it seemed to no longer get sufficiently hot. He postulated that this might be a matter of his own sensory perception rather than an external phenomenon (e.g., a malfunction of the heating pad). His experiment included sampling of the temperature of his skin along with a correlated record of his own sensory perceptions. He concluded the heating pad did function properly.

**Levels of Scientific Sophistication**

The teachers exhibited a wide range of sophistication with respect to their experimental designs. While some were quite expert, a number of teachers’ experiments revealed interesting gaps in their scientific knowledge. For example, the teacher who attempted to resolve the “who takes the hottest bath” question produced graphs that she described as showing water temperature versus time. Yet near the end of her class presentation, she noted that her Cricket apparatus was measuring the air temperature of the bathroom near the tub, rather than the water temperature itself. She had taken the assumption that the two would be so closely correlated that she could use the air temperature reading as a measurement of the water temperature. It may indeed have been the case that the two had a tight correlation, but most of us believed this could not be simply assumed. There were other cases like this: in a sunglasses performance experiment, the teachers desired to confirm the value of polarized lenses, but did not realize that the light sensors do not detect polarization; in a wood deck/patio brick heat transfer experiment, the temperature sensor itself also received direct solar radiation, confounding the measurement of deck or brick heat.

In some projects, teachers began with faulty or incomplete models and evolved them during the course of their projects. In one instance, teachers expected that it would be better to wear white T-shirts in the summer, because white should reflect most of the sunlight’s wavelengths. In their experiments, they
determined that white T-shirts passed light on through to the skin, and that dark T-shirts would be safer from a sun exposure point-of-view.

Conclusions and Future Directions

We were honestly surprised and thrilled with the teachers’ work. We did not expect such a variety of projects, especially given the simplicity of the sensor devices. We did not anticipate the depth of personal connection that many teachers made to their investigations, especially when they worked individually as in the first two years of the project. Many teachers used the project to answer questions for which they genuinely cared about the answer.

The teachers’ work demonstrates that novices can perform analogous work to that done by “real” scientists. Many of the activities and approaches used by real scientists—asking a question, developing apparatus and collecting data, analyzing the data, and iterating—are present in the teachers’ projects. We postulate that as our technology is somewhat “raw” (unpackaged and uncalibrated when compared to commercial classroom data collection systems), teachers were required to do more of the basics, leading to an experience that more authentically demonstrated real scientific inquiry. As such, projects of this type lend themselves to helping teachers and students to better understand the nature of science.

One further outcome of this work—which we had not fully anticipated—was what it revealed about teachers’ scientific reasoning. Many of these new science teachers had not previously been asked to interpret messy data which had no predetermined outcome. In fact, the teachers’ reported that their prior experiences in school-based and college laboratory settings were frequently verification in nature. Anomalous data in such verification lab work are often ignored or dismissed as “experimental error.” No data generated in the Cricket projects could be overlooked because their relevance is not known in advance. Consequently, the demands on teachers’ empirical-inductive thinking were high and it became clear to us, that in spite of possessing undergraduate degrees in science, some teachers had not fully developed the reasoning skills that are essential in inquiry-oriented work.

We plan further studies that will examine how these kinds of explorations support the development of scientific reasoning in both teachers and students.

References