Beyond Black Boxes:
Bringing Transparency and Aesthetics Back to Scientific Investigation

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Abstract

We present a set of case studies in which students create, customize, and personalize their own scientific instruments – and thus become engaged in scientific inquiry not only through observing and measuring but also through designing and building. While computational technologies have, in general, contributed to making today's scientific instruments more "opaque" (that is, less understandable) and less aesthetically-pleasing than their predecessors, we argue that these same technologies can be used to bring back a sense of transparency and aesthetics to the design of scientific instruments. We analyze how students, by building their own scientific instruments, can: pursue a broader range of scientific investigations of their own choosing, feel a stronger sense of personal investment in their scientific investigations, and develop deeper critical capacities in evaluating scientific measurements and knowledge.

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> *“Science, whatever be its ultimate developments, has its origin in techniques, in arts and crafts.... Science arises in contact with things, it is dependent on the evidence of the senses, and however far it seems to move from them, must always come back to them.”*
>
> — B. Farrington, *Greek Science* (1949)

Introduction

Science is popularly regarded as a “cognitive” activity—a discipline of the mind. But there is also a more physical and tactile tradition in science—a tradition in which scientists do not merely measure and theorize but also construct the instruments needed to do so. Indeed, many of the most important advances in scientific history were based on a combination of science, engineering, and design. Galileo’s construction of his own telescope (as described in Galilei, 1610), Boyle and Hooke’s design of the air-pump for experimentation with low pressure (Shapin, 1996), and Kelvin’s construction of a tide-measuring device (MacDonald, 1964) are examples of this tradition and staples of scientific lore. By building their own instruments—and understanding the capabilities and limitations of those instruments—scientists have historically gained deeper insights into the nature of the phenomena under investigation.

The merits of the instrument-building tradition go beyond the immediate needs of research. Indeed, one element of that tradition is a design philosophy that emphasizes elegance and beauty in the material objects of scientific work. One can still witness this aesthetic tradition in museums and archives, in the writings, drawings, and surviving instruments of an earlier era of scientists. Examples are not hard to come by: the timepieces of John Harrison, for instance, represented both revolutionary advances in instrumentation design and gorgeous, intricately decorated works of functional art (Sobel, 1995). Tycho Brahe’s observatory was both a working laboratory and a showpiece of beautiful devices (Rider, 1983, pp. 52-3). And in the annals of computer science, the calculating devices of Pascal and Leibniz, and the 19th-century “analytical engine” of Charles Babbage (as reconstructed in the Science Museum in London), each exhibit their own variety of mechanical beauty. The optical instruments, navigational devices, and glassware of eighteenth and nineteenth century researchers often strike the modern viewer as both functional and eye-pleasing; even the historical tradition of scientific illustration (as exemplified in the drawings of Audubon) combines precision and beauty (e.g., Turner, 1980; Daumas, 1972; Ford, 1993).

The instrument-building and aesthetic traditions of science have arguably been attenuated in recent years—and, in part, for good reason. Science is no longer the province of the individual aristocrat, and the design of scientific instrumentation has increasingly become (like much else in this century) a matter of mass production. While the democratization of science is welcome, the decline of “scientific craftsmanship” is a more problematic phenomenon. In the opinion of some scientists, the experience (and perhaps even the quality) of scientific research suffers when the researcher loses close physical contact with the tools and materials of the trade. As Pierre-Gilles de Gennes (a Nobel laureate in physics) writes,

> *"In rural France of yesteryear, children used to be in daily contact with nature and with the world of craftsmen, which gave them a sense of observation and of manual work.... Access to computer technology is a necessity, but if we are content to sit our young people in front of computer monitors (which they love), we are at risk of losing something precious. To form a generation that knows only how to hit a keyboard and produce reports is, to me, a scary prospect."* (de Gennes, 1996, p. 149)

And there are more subtle problems as well. Over time, the scientific laboratory may, sadly, have become a less beautiful setting in which to work, and a less magical setting to the eye of the student and apprentice. The modern-day student of science is less likely to experience a sense of comfort and delight in their surroundings; and, as Csikszentmihalyi (1996) has observed, the creative enterprise (whether scientific or artistic) is often keenly influenced by just such environmental factors:

> *Even the most abstract mind is affected by the surroundings of the body. No one is immune to the impressions that impinge on the senses from the outside. Creative individuals may seem to disregard their environment and work happily in even the most dismal surroundings.... But in reality, the spatiotemporal context in which creative persons live has consequences that often go unnoticed.* (p. 127)

Both the power and the problem with modern scientific instrumentation are reflected in the term "black box" that is commonly used to describe the equipment. Today's black-box instruments are highly effective in making measurements and collecting data—enabling even novices to perform advanced scientific experiments. But, at the same time, these black boxes are "opaque" (in that their inner workings are often hidden and thus poorly understood by their users) and they are bland in appearance (making it difficult for users to feel a sense of personal connection with scientific activity).

As suggested by the quote from de Gennes, digital electronics and computational technologies have accelerated this trend, filling science laboratories and classrooms with ever more opaque black boxes. Most scientific instruments today are filled with little more than circuit boards and integrated circuits. Even if they opened up the box and looked inside, most students (and even most scientists) would understand very little about how the instrument works.

Paradoxically, the same electronics technologies that have contributed to the black-boxing of science can also be used to reintroduce a vigorously creative, aesthetic, and personal dimension into the design of scientific instrumentation—particularly in the context of science education. This paper describes work that we have undertaken over the past two years as part of our Beyond Black Boxes (BBB) project, focusing on the development of new computational tools and project materials that allow children (and older students) to create, customize, and personalize their own scientific instruments. Our tools and materials make use of tiny, fully-programmable computational devices, called Crickets, that students can embed in (and connect to) everyday objects. Crickets can control motors and lights, receive information from sensors, and communicate with one another via infrared light. Because the Crickets are general-purpose computers, students can reprogram them for use within a wide variety of home-built instruments; because they are tiny, portable, sturdy, and capable of communication with one another, students can employ them in novel or idiosyncratic ways. Crickets thus (on the one hand) expand the traditional landscape of informal instrumentation design, and (on the other) intensify the individual relationship between user and instrument, making it possible to weave scientific inquiry into personally designed (or personally meaningful) artifacts and everyday activities.

The remainder of this paper describes ways in which this new technology can enhance the creative, aesthetic, and personal dimensions of students' scientific inquiries. In the next section, we begin by placing our work in the context of related traditions of science education. The third section provides a brief introduction to Crickets and related technologies. The fourth section—the heart of the paper—describes several case studies of students involved in the creation, embellishment, or personalization of scientific instruments. In the fifth section, we reflect on these case studies, making note of both the positive and negative aspects of the experiences—broadly speaking, what has and has not "worked" in our efforts to move beyond black boxes in science education.

Related Research

Our BBB research effort has been influenced and informed by several related traditions of science education. On the one hand, there is a long and venerable tradition of "home science" books and materials, suggesting experiments and design projects that students can undertake with easily available materials (e.g., Diehn and Krautwurst, 1994; Doherty and Rathjen, 1991; Hann, 1979). Related to the home science tradition is a compelling literature (primarily British) on "design education," in which elementary school classroom projects focus on the creation of devices, machines, tangible models, and so forth (e.g., Banks, 1994; Kolodner et al., 1998; Ritchie, 1995; Williams and Jinks, 1985). Yet another tradition of work employs microcomputer-based lab (MBL) activities, in which computer software and scientific instrumentation are combined to enrich and automate a variety of classroom-based science projects (Tinker, 1996). Finally, we have been strongly influenced by the tradition of work in children's programming (and more broadly, end-user programming), exemplified by the body of work that has grown around the Logo language and its descendants (Papert, 1980).

Our work has been influenced by ideas from all these sources, but at the same time exhibits a combination of features that contrast with any one of these traditions viewed individually:

- *Constructionist approach*. In most MBL activities, students use pre-built instruments; similarly, many "home science" books focus on pre-designed demonstrations and experiments. BBB activities take a different approach: students are encouraged to construct and program the instruments that they use—and to design their own experiments. In our belief, this "constructionist" approach (Papert, 1993) deepens students' understanding of the scientific concepts involved in the activities. This echoes Larkin and Chabay's (1989) dictum for science education, to "let most instruction occur through active work on tasks" (p. 161); similarly, Berger (1994), in his compelling book on the Westinghouse Science Talent Search, observes that "too many schools are satisfied to spend their time imparting the standard biology and chemistry syllabi. Research, though, is the fun part of science, the part that allows for cunning and wonder" (p. 235).

- *Real-world science*. Traditionally, much work involving children's programming in science education has focused on simulation of natural processes. This use of computers has obvious appeal: by programming simulations, students (and researchers) can explore phenomena that are otherwise difficult or impossible to see in the real world—phenomena that involve idealized (e.g., frictionless) conditions, that occur at very large or small scales, or that take place over long periods of time. But simulation, however valuable, is only a part of science education. Ultimately, science is an enterprise devoted to understanding the material world; as such, investigations of real-world phenomena are crucial to students' development of both scientific understanding and scientific interests. BBB activities are thus intended to expand the landscape of children's programming from an exclusive focus on simulation to a deeper involvement with the tangible world outside the computer screen.

- *Combine sensing with control*. In most MBL activities, students collect and analyze data from sensors. Cricket-based activities go a step further: students use sensor data to control the actions of motors, lights, and other electronic devices. The combination of sensors and actuators within scientific instruments likewise represents a step beyond most of the work in both the design education and home science traditions: the former often focuses on the construction of static or mechanical artifacts, while the latter often assumes an exclusively "low-tech" material basis to informal scientific exploration.

- *Programmability*. Unlike most MBL equipment, Cricket-based instruments are fully programmable, so that students can more easily modify, customize, and extend the functionality of the instruments that they build.

- *Mobility*. The small size of the Crickets makes it possible for students to create scientific instruments that they can carry with them, distribute in remote locations, or even embed inside other objects.

- *Low cost*. The low cost of Cricket-based instruments dramatically changes the types of investigations that are possible. Students can put Cricket-based instruments "at risk," placing them in dangerous environments without worrying whether a few of them get lost or damaged. Both the mobility and relative affordability of Crickets can, we believe, effect a sea change in the assumptions of the "home science" and design education traditions, moving those traditions toward a more powerful mixture of computational and craft media. Ultimately, we feel that Crickets (and their computational descendants) can achieve the status of everyday objects—part of the landscape of "stuff" that now includes plastic, wire, cardstock, elastic fabric, and other modern-but-mundane materials.

- *"Daylong Learning"*. Many traditional MBL activities involve experiments that, to students, seem unmotivated and decontextualized. By contrast, our intention is to help students develop investigations that draw on their everyday activities and that, in many cases, involve data collection over extended periods of time. The goal is to shift away from classroom learning to "daylong learning"; the Cricket's small size (along with its ability to store data collected over time) facilitates this shift.

- *Variety of materials.* Typically, BBB activities involve the use of a wide range of materials: electronics, wood, paper, LEGO bricks, foam core, and many others. In this respect, BBB activities share an interest with the "home science" tradition of making creative use of all sorts of objects and resources. Our focus is not, therefore, on using Crickets solely within the context of larger pre-existing construction kits in the tradition of LEGO, Meccano, Fischer-Technik, and so forth; marvelous and versatile as those kits are, we see them as part (an important part) of a larger, more varied world of building materials. The use of a wide variety of materials also lends itself well to a focus on the aesthetics of design.

- *Aesthetics of design.* Traditional MBL and home science activities pay little or no attention to the aesthetics of the instrumentation, or the ways in which instruments are integrated into their surroundings. As scientific investigations extend over longer periods of time and connect to everyday activities, aesthetics become increasingly important. BBB projects are thus often designed with an eye toward decoration, ornamentation, or whimsy, in keeping with the observations of Csikszentmihalyi quoted earlier.

Technology Infrastructure

New technology was needed to support students in the activity of designing and building their own scientific instruments. As part of our Beyond Black Boxes effort, we developed a new family of tiny computational devices called Crickets. The Crickets are somewhat similar to the "programmable LEGO bricks" previously developed at the MIT Media Lab (Martin, 1994; Sargent et al., 1996), but they are much smaller and lighter (the current prototype is roughly the size of a 9-volt battery), and they have enhanced communications capabilities. Crickets can control motors, receive information from sensors, and communicate with one another (and other electronic devices) via infrared communications (Resnick et al., 1998).

Most important, the Crickets are fully programmable: students can write and download computer programs into the Crickets from a desktop computer. We have extended our previous development of Logo-based programming environments, with a goal of making it even easier for students to write (and understand) control- and sensing-oriented computer programs. At the same time, we have made these programming tools compatible with graphing and analysis software "components," so that students can easily investigate trends and patterns in the data that they collect with their Crickets.

The small size of the Crickets opens up new types of applications. Students can embed Crickets inside everyday objects—for example, a Cricket with an accelerometer may be embedded inside a ball, or a Cricket and temperature sensor may be woven into the fabric of a shirt. The low cost (less than $30 for the current version) and communication capabilities of the Crickets make it possible to imagine new applications involving dozens of Crickets interacting with one another.

We believe that computational technologies (such as the Crickets) are particularly appropriate for bringing aesthetics considerations back to scientific instruments, since they enable a separation of the form of a tool from its function. In the past, the function of a tool was directly tied to its physical form. For example, the function of a hammer is closely linked to its shape and materials. With computational technology, there is a loosening of the binding between form and function. The software in a Cricket can play a larger role in determining the tool's function than the tool's physical shape or materials. No longer held hostage to functional constraints, the forms of objects can now be used specifically for communication and expression.

Of course, Crickets are only one component of the construction kits that we provide for BBB projects. Many BBB projects make use of LEGO materials (including not only the traditional building blocks but also gears, wheels, and motors) for building structures and mechanisms. We provide a variety of different sensors that enable users to monitor everything from temperature and light to heart rate and galvanic skin response. We have also developed a collection of new output devices (in addition to motors and lights), such as numeric displays and "music bricks" for generating sound effects. Just as important as these "high-tech" devices are artistic materials. When organizing BBB activities, we make sure to supply a wide range of arts-and-crafts materials, including everyday objects such as pipe cleaners, popsicle sticks, and cotton balls. This blend of high-tech devices and art supplies makes possible precise explorations and investigations while simultaneously fostering a spirit of creativity, exuberance, humor, stylishness, and personal expression.

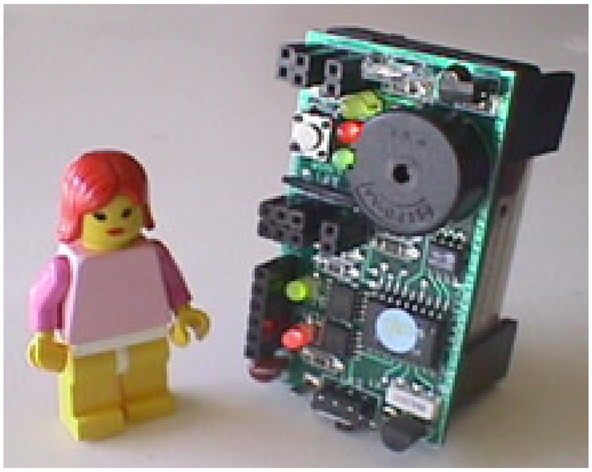

Figure 1: Cricket (with LEGO figure shown for scale)

Case studies

We have tested our Beyond Black Boxes technologies and activities at a diverse collection of educational settings, including not only traditional school classrooms but also after-school learning centers for inner-city youth. We have also worked with learners of different ages, from elementary-school children to university students. In this section, we offer four case studies of BBB projects. These case studies are not intended to suggest the complete range of BBB projects. Rather, they are intended to provide a representative sampling of how and what students learn when they are engaged in designing their own scientific instruments and investigations.

Bird Feeder

Jenny, 11 years old, loved all types of animals. In her backyard she had a bird feeder which she kept stocked with food for the local birds. But there was a problem: often, the birds would come while Jenny was away at school, so she didn't get to see the birds. So when she began working with Crickets at the Build-It-Yourself Workshop (an after-school center organized by John Galinato), Jenny decided to try to build a new type of bird feeder that would collect data about the birds that landed on it.

Jenny started by making a wooden lever that served as a perch for the birds (Figure 2). The long end of the lever was next to a container with food for the birds. At the other end of the lever, Jenny attached a simple home-made touch sensor consisting of two paper clips. Jenny's idea: When a bird would land near the food, it would push down one end of the lever, causing the two paper clips at the other end to move slightly apart. Jenny connected the paper clips to one of the sensor ports on a Cricket, so that the Cricket could detect whether the paper clips were in contact with one another.

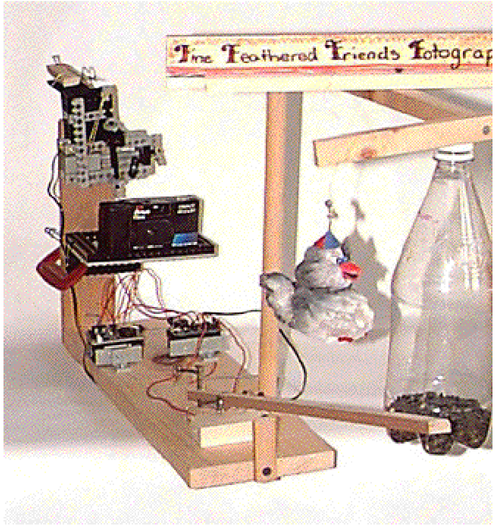

Figure 2: Jenny's bird feeder

But what should the bird feeder do when a bird landed on it? At a minimum, Jenny wanted to keep track of the number of birds. She also thought about weighing the birds. But she decided it would be most interesting to take photographs of the birds. So she began exploring ways of connecting a camera to her bird feeder. She built a motorized LEGO mechanism that moved a small rod up and down. She mounted the mechanism so that the rod was directly above the shutter button of the camera.

Finally, Jenny plugged the mechanism into her Cricket and wrote a program for the Cricket. The program waited until the paper clips were no longer touching one another (indicating that a bird had arrived), and then turned on the motorized LEGO mechanism, which moved the rod up and down, depressing the shutter button of the camera. At the end of the day, the camera would have pictures of all of the birds that had visited the bird feeder.

Jenny worked on the project for several hours a week over the course of three months. By the end, the sensor and mechanism were working perfectly. But when she placed the bird feeder outside of her window at home, she got photographs of squirrels (and of her younger sister), not of birds.

Jenny never succeeded in her original plan to monitor what types of birds would be attracted to what types of bird food. But the activity of building the bird feeder provided a rich collection of learning experiences. In Beyond Black Boxes projects, science and technology can interact in two ways. The most obvious connection is the way students use technological instruments to make scientific measurements—as in Jenny's (never completed) plan to use her bird feeder to monitor bird activity. Perhaps less obvious, but equally important, is the way students use scientific knowledge to build their technological instruments. In the case of the bird feeder, Jenny needed to experiment with different lever designs to achieve the necessary mechanical advantage for triggering the paper-clip touch sensor. Jenny also systematically experimented with the placement of her camera, testing it at different distances from the bird perch in an effort to optimize the focus of the photographs. Thus, the bird-feeder activity provided Jenny with an opportunity to make use of scientific concepts in a meaningful and motivating context.

The transparent[1] nature of the bird feeder put Jenny in closer contact with the technology—and with the scientific concepts related to the technology. Consider Jenny's touch sensor. In general, touch sensors are based on a very simple concept: they measure whether a circuit is open or closed. People interact with touch sensors (in the form of buttons) all of the time. But since most touch sensors appear in the world as black boxes, most people don't understand (or even think about) how they work. In Jenny's touch sensor, created from two simple paper clips, the completing-the-circuit concept is exposed. Similarly, Jenny's LEGO mechanism for pushing the shutter of the camera helped demystify the control process of the bird feeder; sending an infrared signal from the Cricket to trigger the camera might have been simpler in some ways, but also less illuminating.

Of course, not everything in Jenny's bird feeder is transparent. The Cricket itself can be seen as a black box. Jenny (and other students working on BBB projects) certainly did not understand the inner workings of the Cricket electronics. But that was not the goal. As we designed the "construction kits" out of which students would create their BBB projects, we made explicit decisions to hide certain processes and mechanisms within black boxes, while making other processes and mechanisms visible and manipulable. The choices of which features to hide—and which to highlight—were guided by our desire to make certain concepts particularly salient and accessible for students. Our hope was that students would naturally "bump into" some concepts (and avoid getting distracted by others) as they worked on their projects. Black boxes are not inherently bad; the challenge is to find the right "level" for the black boxes, hiding unnecessary detail while highlighting key concepts. For example, while the Cricket's electronic circuitry remains hidden, Jenny was able to directly control the rules underlying the functioning of her bird feeder. Through the course of her project, she continually modified her Cricket Logo programs to extend the functionality of the bird feeder. After finishing the first version of the bird feeder, Jenny recognized a problem: If a bird were to hop up and down on the perch, the bird feeder would take multiple photographs of the bird. Jenny added a `wait` statement to her program, so that the program would pause for a while after taking a photograph, to avoid the "double-bouncing" problem.

This ability to modify and extend her project led Jenny to develop a deep sense of personal involvement and ownership. She compared her bird-feeder project with other science-related projects that she had worked on in school. "This was probably more interesting cause it was like you were doing a test for something more complicated than just what happens if you add this liquid to this powder," she explained. "It was more like how many birds did you get with the machine *you* made with this complex thing you had to program and stuff" [emphasis hers].

The Chocolate Walk

We have developed a variety of initial activities to help introduce students to the ideas underlying the BBB project. One of the most successful (and popular) has become known as "the chocolate walk." This activity was first developed for a BBB workshop one February, with a group of fifth-grade girls at the Patriot Trail Girl Scout Center in Boston. We gave each girl a Cricket with a temperature sensor, and showed the girls a program for recording temperature data at regular intervals. The girls took the Crickets

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[1] We describe an object as "transparent" when its inner workings are easily seen and understood. Ironically, some people have recently begun to use the word "transparent" with an almost opposite meaning, to describe objects that are so easy to use that you don't even need to think about their inner workings.

and sensors with them as we went on a walk outside to a local donut shop. Some girls attached the sensors to their clothing. Others held the sensors in their hands and touched the sensor to various objects along the way. At the donut shop, all of girls got a cup of hot chocolate. In unison, all of the girls touched their temperature sensors to the sides of their cups (and some dunked the sensors into the hot chocolate itself).

After returning to the Girl Scout Center, the girls uploaded their temperature data from their Crickets to desktop computers, then used graphing software to plot the temperature over time. The resulting graphs, in effect, told the story of the walk to the donut shop. The girls could see, on their graphs, when they had left the warmth of the Girl Scout Center onto the chilly downtown street. For those girls who just wore their sensors, the graphs were relatively flat and featureless until they reached the donut shop. For girls who had used their temperature sensors to touch objects along the way, there were spikes and other variations in the graphs. All of the graphs showed a rise in temperature as the girls entered the donut shop, then another spike when the girls touched their sensors to their hot-chocolate cups. After examining their individual graphs, the girls gathered around a common computer and uploaded their Cricket data to a single computer, so that the graphs could be superimposed. In this way, the girls were able to examine the ways in which their graphs were similar (e.g., the hot-chocolate spikes all occurred at the same time) and the ways in which they were different.

With this activity, the girls learned some of the basic concepts of data collection and analysis. We have found that collection of temperature data is a particularly effective approach for introducing students to these ideas. Children bring a great deal of experience and intuition related to temperature. They grow up hearing the temperature on television and radio and in everyday conversation. They are familiar with thermometers, and they have a “feel” for different temperature readings—knowing that they need to dress warmly if the temperature is in the 20s and that they can go swimming if it is in the 80s. Because of these well-developed intuitions, students are in a good position to evaluate the “reasonableness” of the data they collect and graph, in contrast to many classroom science experiments in which students start with relatively weak intuitions about the data being collected.

Of course, we are not the first to notice children’s knowledge and intuitions about temperature. In recent years, many researchers and educators have developed projects around the topic of weather, hoping to leverage students’ interest and knowledge about weather (e.g., Pea, 1993). In some cases, students set up computer-based “weather stations” at their schools to measure temperature, humidity, and other weather conditions over time.

At a surface level, such projects seem almost identical to the chocolate walk; in each case, students collect and analyze a set of temperature data over time. But we see several important differences. Crickets allow for more individualized monitoring and analysis. In the chocolate walk, the graphs tell a different (and personalized) story for each participant. Each girl was able to identify, on her graph, when *she* walked outside, when *she* put her sensor inside her friend’s coat, when *she* dunked the sensor in her hot chocolate.

The chocolate walk, in contrast to traditional weather-monitoring activities, introduces a sense of control over what is being measured. As the old saying goes: “Everyone talks about the weather, but no one can do anything about it.” In monitoring weather, students are just passive observers. In the chocolate walk, students decide which temperatures to measure and when. Another difference is the time scale of the activities. In traditional weather-monitoring activities, interesting patterns emerge only over the course of days or weeks. The chocolate walk works well as an introductory activity since students can see interesting stories in temperature data over much shorter time frames.

One of the attractions of the chocolate-walk activity is the way in which it aligns with students' existing intuitions, so that students can easily see stories in the graphs. At the same time, this type of activity often yields unexpected surprises in the data—which students are able to recognize precisely because most of the data is so familiar. These surprises can arise in even the simplest of investigations.

On one cold day, for example, a group of us wore temperature sensors as we traveled from the MIT Media Laboratory to the Computer Clubhouse at The Computer Museum in Boston. The trip involved walking from the Media Lab to the subway stop, taking the subway for four stops, then walking for a few blocks to the museum. We had made this trip many times in the past, so we thought we knew exactly what type of graph we would get. When we uploaded the data from our Crickets, many features of the graph were, in fact, just as we expected (Figure 3). The temperature went down as we left the Media Lab, went up as we walked through another MIT building, went down as we went outside, rose as we entered the subway, and fell as we left the subway, and finally rose again as we reached the Clubhouse. But even if the overall contour of the graph met our expectations, something about the graph seemed very strange. We were surprised that the subway portion of the graph was so brief. In our minds, most of the trip to the Clubhouse was on the subway—and, indeed, the subway ride accounted for most of the *distance* of the trip. But the graph showed that, contrary to our intuitions, most of the *time* of the trip was spent walking.

We have found that such surprises are more the rule than the exception in these "everyday data collection" activities. We have often encouraged students to take Crickets home to collect data overnight. One 11-year-old girl left her Cricket in the kitchen overnight and was surprised to see a temperature spike at 2:00 am. After some detective work, she deduced that her Cricket, which she had placed on top of the microwave oven, had caught her father making popcorn in the middle of the night. Another class of fifth-grade students put Crickets with temperature sensors and light sensors in their family bathrooms. By examining when the bathroom lights were turned on and off, the students observed patterns in how their families used the bathrooms. Less expected, students found that they could use the temperature data to tell when family members were taking showers.

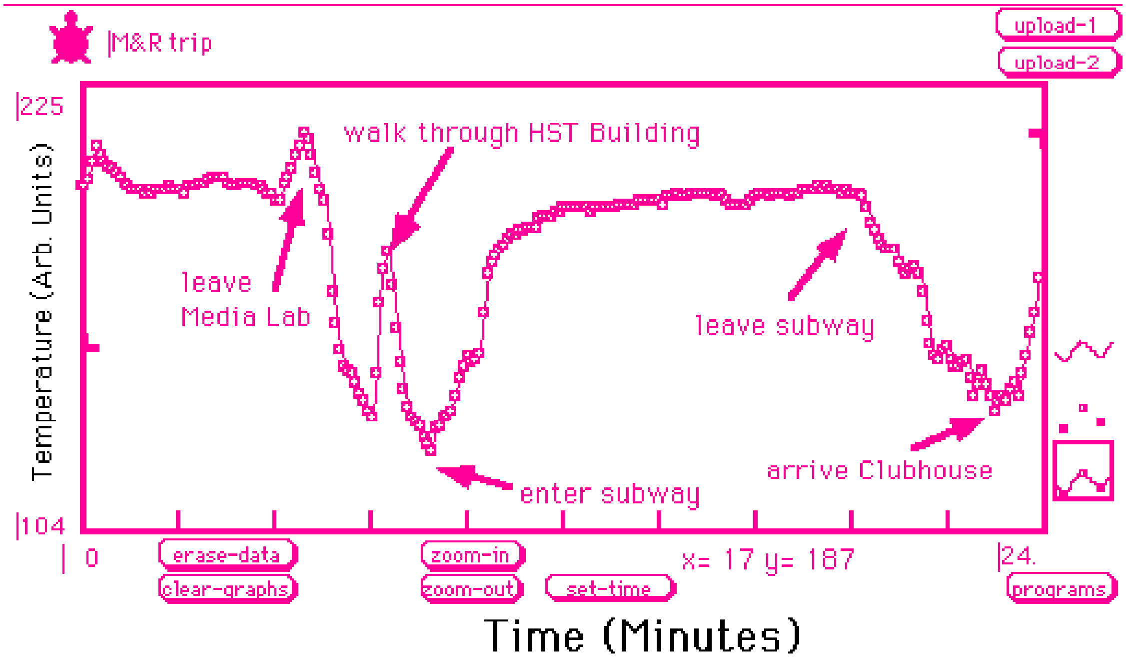

Figure 3: Trip to the Clubhouse

These overnight experiments can reveal patterns not only in human activity but also in technological activity. In several classes, students left Crickets with light and temperature sensors in their family refrigerators. As expected, the data revealed when family members opened the refrigerator door. But the data also contained some real surprises. Students expected the refrigerator temperature to be constant in the middle of the night, when no one was using the refrigerator. But, in fact, the temperature graph had a cyclical pattern, moving up and down in regular intervals. The reason: Refrigerators use thermostats that allow the temperature to rise several degrees before restarting the compressor, which then stays on until temperature drops to a designated level. Thus, while students devised their experiment in order to monitor an activity with which they were very familiar (human use of the refrigerator), they ended up gaining an understanding of a scientific concept (feedback) that is typically not addressed in pre-college curricula.

Marble Machines

While working at the Science Museum of Minnesota, Karen Wilkinson and Mike Petrich organized various types of design workshops for kids. In one workshop, dubbed "mini-mini golf," kids designed and built small-scale versions of miniature-golf courses—using Styrofoam and cardboard to create the structures, motors to animate the obstacles, and marbles instead of golf balls. In another workshop, kids created "marble machines"—whimsical contraptions in which marbles would careen down a series of ramps and raceways, bouncing off bells and bumpers.

When Karen and Mike heard about the BBB initiative, they decided to extend their work on marble machines, adding Crickets, motors, and sensors to the bin of construction parts. The goal was to help kids create new types of kinetic sculptures, bridging the worlds of art and technology. They organized their new marble machine project at the Computer Clubhouse in Boston, working with a group of 10-12 year olds.

Alexandra, a fifth grader, became interested in the marble-machine project right away. She started by cutting wooden slats to serve as ramps; it was the first time she had ever used a saw or vice. She inserted the ramps into a peg-board and began rolling marbles from one ramp to another. Next, she created a Cricket-controlled conveyor belt with a small basket on top. Her plan: the marble should roll down a ramp into the basket, ride along the conveyor belt inside the basket, then drop onto the next ramp when the basket tipped over at the end of the conveyor belt. How would the conveyor belt know when to start moving? Alexandra programmed the conveyor-belt Cricket to listen for a signal from another Cricket higher up on the peg-board, alerting it that the marble was on its way. The conveyor-belt Cricket waited two seconds, to ensure that the marble had arrived safely in the basket, before starting to move the conveyor belt and basket (Figure 4).

Alexandra was excited about her project and decided to enter it into her school's science fair. But when she talked to her classroom teacher about it, the teacher said that the marble machine was not acceptable as a science-fair project. The teacher explained that a science-fair project must use the "scientific method": the student must start with a hypothesis, then gather data in an effort to prove or disprove the hypothesis. The marble machine, said the teacher, didn't follow this approach. In addition, science-fair projects must include references from the library, and Alexandra was not able to find any references to "marble machines" in the school library. As an alternative, the teacher suggested that Alexandra investigate whether it is possible to grow plants in Coca-Cola.

Alexandra decided to stick with the marble machine. With support from Karen and Mike, she put together a sequence of photographs showing different phases of the marble-machine construction. Even though Alexandra never wrote a hypothesis for her project, her teacher ultimately relented and allowed her to enter the marble machine in the school science fair. Much to Alexandra's delight, she was awarded one of the top two prizes for the entire school.

Figure 4: Alexandra's marble machine

The story of Alexandra's marble machine raises important issues about the nature of scientific investigation. While we certainly agree that science education should aim to help students gain an understanding of the scientific method, we believe that many educators (including Alexandra's teacher) adopt too narrow a view of the scientific method. Indeed, we view Alexandra's project as a wonderful example of the scientific method. Although Alexandra did not start with a single overarching hypothesis, she was continually coming up with new design ideas, testing them out, iterating based on the results. Each of these design ideas can be viewed as a "mini-hypothesis" for which Alexandra gathered data. Over the course of her project, she investigated literally dozens of these mini-hypotheses—even if she did not explicitly view them as such.

While positioning the ramps, for example, Alexandra tested different angles to see try to find the maximum range for the marble. Alexandra also experimented to find the right timing for the conveyor belt. She modified the conveyor-belt program so that the basket would make one complete revolution, returning to its original location, properly positioned for the next marble.

This type of experimentation contrasts with ways inclined planes and balls are used in traditional science-classroom experiments. Rather than simply gathering data on the speeds and timing of descent for different angles, Alexandra ran her mini-experiments within a broader (and more meaningful) design context.

Artistic Displays

The final case study involves the work not of an elementary-school student but of an undergraduate student, Adrienne Warmack, in the school of architecture at the University of Colorado. Her project was to focus on the aesthetic side of instrumentation design, creating "artistic" measurement devices. One of her creations was a light meter created in the shape of a flower. This device was simple in principle: it employed a Cricket with a light sensor and motor output. The sensor, upon recording a level of light beyond a user-defined threshold, would activate the motor output, in turn pushing a shaft that opened a set of large, foam-core "petals." When the light level returned to a low value, the motor would turn in the opposite direction, "closing" the flower. (Figure 5 shows the device in various stages of operation.)

Figure 5: The "flower" light meter

Another of Warmack's creations was a device for displaying current paths in closed circuits. This device employed a sheet of temperature-sensitive material which changes color in response to a temperature shift of approximately 5 degrees Centigrade (from a starting point of room temperature). The temperature-sensitive material was placed in a circular frame so that it looked rather like the surface of a drum; directly underneath the material were criss-crossing patterns of wires from which metal leads descended. Underneath this entire apparatus, a Cricket was used to turn a set of positive and negative leads (attached to a DC battery); when the Cricket turned from one position to another, distinct complete circuits were created through the set of wires sitting underneath the temperature-sensitive material. As current ran in these circuits, the wires involved in the circuit would heat up and the material would change color in patterns that revealed the current running directly underneath. Figure 6 shows several snapshots of the device in operation.

Figure 6: The current display device

In both of these sample creations, the scientific content is relatively straightforward: one device is a prototype for a light meter, the other a display device for current running through a wire. To end the analysis here is to miss the point, however: such devices are not intended simply as measurement devices, but as occasions for artistic ingenuity and whimsy. Indeed, these two devices illustrate the rich possibilities of blending art and instrumentation design. As we have observed students creating their own scientific instruments, we have been struck by how students seem to form a much stronger connection with their instruments (and with the overall activity) when they pay attention not just to functionality but also to aesthetics.

These two devices reflect the wide range of materials that have become available for the purposes of home scientific crafts—materials ranging from portable computers (the Crickets themselves), sensors, and innovative materials to plastic toy pieces and “low tech” wooden blocks. The light meter made use of a wooden frame, metal piping, and foam-core “petals” (in addition to the Cricket and LEGO pieces); the current display device made use of a novel material (the temperature-sensitive film) that is available from science-education catalogs at a moderate cost. Where, for a previous generation, “home science” would often imply a relatively narrow range of simple working materials, the combination of Crickets and a burgeoning world of new materials has opened new possibilities for informal scientific creation (Eisenberg and Eisenberg, 1998).

We have found that BBB projects provide a natural way for students to explore issues related to the concept of “representation.” As students build displays (such as the flower light meter and the current display), they need to think through the most effective way to represent the information that they want to convey. For example, at the Build-It-Yourself workshop, Luke decided to build a display for Jenny’s bird feeder. He wanted to make it easy for people to find out how many birds had come to the feeder that day. At first, he created a type of “audio representation.” He programmed the Cricket to keep track of the number of birds that landed and built a new button on the bird feeder. When you pressed the button, the Cricket would indicate the number of bird visits by beeping the appropriate number of times. This representation worked fine when the number of bird visits was a small number like 2 or 4 or 5. But when the number of bird visits was higher, the representation was awkward: the user would have to count carefully (and for a long time). So Luke decided to use two different pitches of beeps: a high pitch for the “tens” and a low pitch for the “units.” To indicate 42 bird visits, the Cricket would sound four high-pitched beeps followed by two low-pitched beeps. This new representation had some clear advantages, but Luke then decided that a spatial readout would be better than a temporal readout (the beeps). So he built two dials (one for the tens and one for the units), each controlled by a separate motor. The button was no longer needed: the dials could continuously display the number of bird visits. In many other BBB projects, students have gone through a similar process of exploring alternative representations. Many research studies (e.g., diSessa et al., 1991) have documented the value of this type of meta-representational activity, in which learners construct (and reflect on) new forms of representation.

Reflections

Increasingly, science educators are recognizing the value of learners designing their own scientific investigations (rather than replicating well-known experiments). Through our case studies, we have tried to demonstrate that *designing your own tools* can be a particularly important component to *designing your own investigation*. Too often, this idea is overlooked. In its influential National Science Education Standards (1996), the National Research Council lists "using tools to gather, analyze, and interpret data" as a core component of scientific inquiry (p. 23). We certainly agree. But we go a step further, arguing that it is critically important for students to have the opportunity to design their own tools (not just "use" pre-existing tools). Our BBB case studies point to several reasons for the value of this design-your-own approach:

- *Extending the space of possibilities*. When students try to design their own scientific investigations, they are often limited by the capabilities of the available instruments. In many cases, standard scientific instruments are simply not well-suited to the investigations that students want to pursue. The BBB solution is for students to create their own instruments, tailoring the instruments to the desired investigation. Jenny certainly could not have walked into a store and bought a picture-taking bird feeder. For many of the investigations that students choose, the small size and mobility of the Crickets are particularly important. By freeing students from laboratory-bound experiments, the Crickets open up new categories of investigations, as in the Chocolate Walk.

- *Motivation*. We have found that students often feel a strong sense of personal investment in a scientific investigation when they design the scientific instruments themselves—particularly, if they add their own aesthetic touches to the instruments. When Alexandra first heard about marble machines, she knew that she wanted to build her own marble machine as a science-fair project: "I thought it would be interesting and different from the other kids' [projects], like from the solar system or the body. It was kind of strange, but fun." Jenny cared about her bird feeder (and the photographs that it took) in large part because she had designed and built it. The "fun part" of the project, she explained, "is knowing that you made it; *my* machine can take pictures of birds" [emphasis hers].

- *Developing critical capacity*. Too often, students accept the readings of scientific instruments without question. When students design their own instruments and investigations, we have found that they develop a healthy skepticism about the readings—and a better understanding of what readings are reasonable and why. When students got "strange" or unexpected readings during everyday data-collection activities (such as the Chocolate Walk), they developed the ability to sort through various possible explanations. In some cases, they concluded that some piece of their equipment had malfunctioned. In other cases (as in the example of the father who made microwave popcorn in the middle of the night), they discovered an initially-unknown event to account for the unexpected data. In still other cases (as in the cyclical patterns observed in refrigerator temperatures), students learned about underlying processes of which they had previously been unaware.

What Didn't Work

The case studies highlight some of the strengths and successes of the BBB initiative. But it is also useful look at the problems and difficulties encountered. Some of the problems have been technical in nature, and have been reasonably easy to fix. For example, the Crickets do not have built-in displays, so it was initially difficult for students to get real-time feedback (on values of sensors, state of the program, etc.) when using Crickets away from a desktop computer. We have started to address this problem by developing a small numeric display as a peripheral for the Cricket, so that students can get readings from the Cricket at any time, in any place. Similarly, we have continued to improve the programming environment for the Crickets to make it easier for students to program new behaviors for their BBB constructions.

The most difficult problems, however, do not have simple technical fixes. BBB activities tend to be especially challenging since learners are involved in multiple types of design: designing investigations while also the designing the tools needed to conduct those investigations. And even the tool-design process itself involves multiple types of design: designing structures, mechanisms, and programs. And, as part of the BBB effort, we have encouraged students to consider not only the functionality but also the aesthetics of the tools they design. We have found that, as a result of these multiple design challenges, students often succeed with one part of a project but have difficulty putting all of the pieces together.

To help students cope with the multiple design dimensions, we have developed introductory activities that involve only some of the dimensions. In some of the everyday data-gathering activities, for example, students design their own investigations without focusing on tool design. Another approach is to start with a focus on the design of tools rather than investigations; for example, we have engaged students in building kinetic sculptures—works of art incorporating Crickets, motors, lights, and sensors. This approach can help students begin to develop their own scientific instruments. One group of high-school students built a sculpture with a motor and light sensor, and programmed the sculpture to move in different directions and speeds based on the light levels detected by the sensor. As they walked down the hall with their sculpture, and saw its motion change as them moved in front of different doorways, they realized that their sculpture could function as an effective light meter—with a much more interesting "display" than traditional light meters. But it is still a big step to go from designing instruments to designing investigations. Part of the challenge is to help students find investigations that they care about as deeply as they care about their kinetic sculptures. Many students, in their BBB activities, did not follow through on data analysis unless they truly cared about the data they were analyzing.

These types of activities also face significant logistical and organizational constraints. As with other design-based and project-based educational initiatives, BBB activities do not fit easily into standard school structures, cutting across traditional disciplinary boundaries and making special demands on time and space. At one BBB research site, students were able to work on their projects just one afternoon a week, and they needed to spend large chunks of their time setting up and putting away their projects. The same site hosted a summer workshop at which students spent full days working on projects each day for three weeks. Students at the summer workshop made substantially more progress on their projects and clearly enjoyed the experience much more.

Beyond Black Boxes

Whereas a previous generation of scientists became hooked on scientific investigation by taking apart their radios, today's children see little that they can understand when they open up their radios and other modern electronic devices. James Gleick (1992) alludes to this phenomenon in his biography of Richard Feynman:

> *Eventually the art went out of radio tinkering. Children forgot the pleasures of opening and eviscerating their parents' old Kadettes and Clubs. Solid electronic blocks replaced the radio set's messy innards—so where once you could learn by tugging at soldered wires and staring into the orange glow of the vacuum tubes, eventually nothing remained but featureless ready-made chips, the old circuits compressed a thousandfold or more. The transistor, a microscopic quirk of silicon, supplanted the reliably breakable tube, and so the world lost a well-used path into science.*

There is little doubt that computers have made the workings of the world less "transparent" for many people. But that need not be the case. In our initial BBB studies, we have seen how students, helped by new computational tools, can build their own customized instruments and begin to view scientific investigation as a process in which they can take part, day-to-day, creatively and pleasurably. Our work so far is just a first step. In future research, we plan to focus on more fine-grained studies of how and what students learn when they design their own instruments and investigations, and on studies of how to make these types of activities succeed in a broader range of settings.

How will we gauge the long-term success of our project? Our ultimate goal is to contribute to the development of a new generation of students who are more likely to "look inside" the technological artifacts in the world around them—and feel empowered to develop their own tools (even very simple tools) for exploring phenomena in their everyday lives.

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