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Robotic Jewelry: Inventing Locally Contextualized Mathematics in a Fourth Grade Classroom

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Abstract. This paper describes a design activity carried out in a 4th grade classroom over an academic year. 18 students and 3 adult participants (the classroom teacher, an engineer, and a researcher) collectively designed and built programmable, electronic necklaces that displayed personality correlations. The overall design was then implemented in the programmable necklace hardware (with the master program was written by the engineer and researcher). Broadly, the activity involved children in a significant engineering design project that crucially used mathematical analysis and software programming in its implementation. The project participants collaboratively developed a local mathematical framework for representing survey answers, correlations between pairs of individuals, and an algorithm (based on Boolean algebra) for computing correlations. Children saw the design unfold over the course of the project, were involved at multiple levels, and became intellectual and practical owners of the resulting system.

1 Introduction

For scientists, mathematics is used to model and understand the world. Engineers use mathematics when designing systems that are then constructed and brought into being. To these individuals, mathematics is an active, living thing. Mathematics provides a set of ways of thinking that is empowering—allowing one not only to make sense of the world, but also to create new inventions that would not be possible otherwise.

Children in school rarely directly experience or even observe this dimension of mathematics. In the typical problem-solving curricula, students are asked to apply decontextualized rules they have learned to solve word-problems. The implicit assumption is that if students learn enough rules and formulas, they will know which ones are appropriate in an actual real-world situation.

Leading mathematics educator Richard Lesh has turned this logic on its head with an approach that he calls "model-eliciting activities." Instead of traditional word problems, where "students make meaning of symbolically described situations," in Lesh's model-eliciting activities, "students make mathematical descriptions of meaningful situations" [2].

As Lesh explains, the difference between model-eliciting activities and traditional textbook word problems is that, in textbook problems, "the main thing that is problematic for students [is] to make meaning of symbolically described situations. Whereas, for the kinds of problems that are emphasized by [model-eliciting activities], almost exactly the opposite kind of processes are problematic. That is, model-eliciting activities are similar to many real life situations in which mathematics is useful. Students must try to make symbolic descriptions of meaningful situations" *ibid.*, pp 3–4.

Here, we describe a design and engineering activity conducted as a collaboration between a classroom teacher, an engineer, a computer scientist, and a class of 18 fourth grade students. In this collaboration, the students were part of a joint design activity in which the group created computationally-active personality correlation necklaces. In the course of the work, students were part of a design process that used mathematics and programming to bring an idea into being. Students were given miniature computer devices ("Handy Crickets") that they used to control their own necklace that they built themselves. Student work was authentically woven into the design process. At the end of the project, students demonstrated the project in two public events, and several of them demonstrated deep fluency in discussing the mathematical ideas embedded in the technology with interested adult visitors.

In this project, our style of work is wholly in concert with Lesh's core values. We proposed to ourselves and our students, "let's build a set of necklaces that reveal personality matches," and then we invented the mathematics that were necessary to carry this out. Furthermore, we actually did build the necklaces, thereby bringing the model to life in the form of physically embedded computing devices. And perhaps most importantly, the whole process was done as a joint venture between the project leaders (the authors) and the 4th grade children. In a significant fashion, we worked with the children as partners, not just students.

Both in terms of personnel and materials, we realize that exceptional resources were made available to this classroom. Our intent in presenting this work is not to offer it as a model for broad replication. Instead, we present it as a successful example of a collaborative process. Rather than the specific activity we conducted, we would like to see the core ingredients of this process to repeat. These ingredients are based a constructive mathematical design experience that is participated in by the classroom teacher and its students, a physical and computational implementation, and public exhibitions and discussions of the results. Using a mathematical foundation, we created an innovative, original, and meaningful artifact, and in the process, developed and reinforced students' mathematical thinking.

2 Why Robotic Jewelry?

Co-author Mary Lurgio is a progressive educator who has been conducting whole-class design projects in her elementary school classroom for many years. For Lurgio, the Robotic Jewelry project drew inspiration from the "Thinking Tag," a prototype that had Martin brought to a summer teachers' workshop.

In the Thinking Tag demonstration [1], 200 guests at a sponsor meeting were each given small, electronic nametags. Guests programmed answers to each of 5 multiple-choice questions into their own tag. When two guests faced each other during causal conversation, their tags would activate and flash LEDs that indicated their "degree of match." Guests would see a green LED for each question they answered the same, and a red LED for each question they answered differently. (The tags didn't tell you *which* questions you had matched or differed on—the point was to encourage a conversation!)

Lurgio has extensive prior experience with using Logo programming and LEGO/Logo robotics with her students. She conceived of the Robotic Jewelry project—robotics for the boys, and jewelry for the girls—and recruited collaborator, engineer, and educator Denis Coffey and researcher Fred Martin to join her in the endeavor.

The project took place over the 2002–2003 academic year in Lurgio's 4th grade classroom at the Anna M. McCabe Elementary School (Smithfield, RI). This paper describes the project, focusing on the mathematics and programming that became embedded into the design process. There were five key components of the activity:

1. Foundational programming work, using the LEGO Control Lab robotics system (Fall 2002)
2. Survey design and mathematical representation (January 2003)
3. Cricket and lamp programming work (February 2003)
4. The necklace construction, and development of the overall control program (March 2003)
5. Project integration and public demonstration (April–May 2003)

In the next section, these major project segments are discussed.

3 Collaborative Classroom Design and Implementation

In chronological order, this section presents the series of classroom activities that comprised the Robotic Jewelry project.

3.1 Foundational Robotics and Programming

In the fall portion of the academic year, students were introduced to robotics construction and programming using LEGO Control Lab. This activity was led by Coffey. Students built simple vehicles and programmed them to move forward and backward. They learned how to issue commands to make the vehicles move for a specified period of time, and thought about the relationship between movement duration and distance traversed. Students were introduced to motors, gears, LEGO design, and programming.

This work would typically be considered as a conventional elementary school robotics activity [3]. But these activities would gain additional meaning in students' subsequent work in the Robotic Jewelry project. When we began the project, students were already familiar with the Logo language and the deeper concept of a computer carrying out the instructions embodied in their own programs. They were ready for more advanced work.

Fig. 1. Three students' list of permutations to 4-question, Y/N survey. Note that the left-most list has 25 entries, so there must be duplications. In all three cases, however, the students used an idiosyncratic method to generate their list of permutations, with no evident algorithm having been employed.

3.2 The Survey Questions

Work started on the Robotic Jewelry project itself in January 2003. Lurgio started out by introducing the children to the Thinking Tag concept. Instead of making lapel tags, the class would be building necklaces that could communicate with each other and would create different sorts of "displays" depending on the correlation between two wearers.

Rather than the 5 questions used in the Thinking Tag project, Lurgio determined that the class would work with 4 yes-or-no questions. The class brainstormed, and four questions were developed. These were chosen so that students could learn a bit of innocent personal knowledge about each other. The following questions were selected:

1. Are you a girl?
2. Are you left-handed?
3. Do you have pets?
4. Are you 9 years old or younger?

Note that the answer to question 1 is more or less self-evident; that is, two people engaging in conversation typically know each others' gender by direct observation. Also, for question 4, when a child talks to an adult, the child knows the adult is not less than 10 years old. (The 4th grade class contained a mix of 9- and 10-year-olds.) Thus, the answers to some but not all of the questions can be known directly. This factor would come into play when students presented the project to adults in the public forums, as will be discussed near the end of the paper.

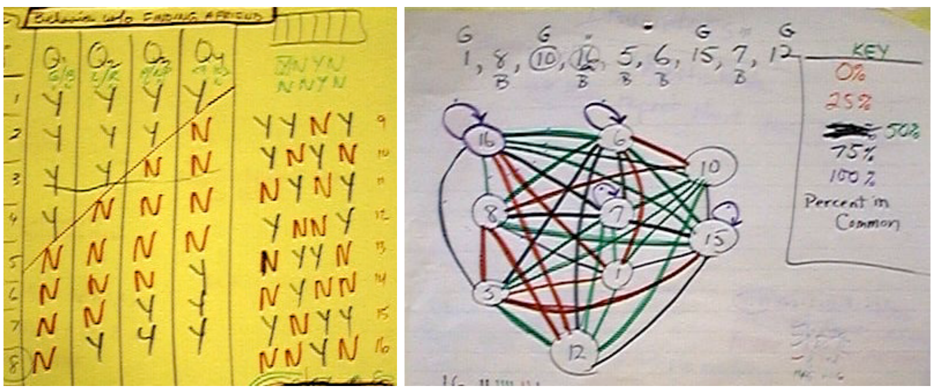

Fig. 2. Lurgio's charts of all 16 permutations of yes/no answers (left), and percentage of match that correlates various pairs of permutations (right). The graph links on the right-hand chart are color-coded to represent percent-of-match; thus, information may be lost in this presentation.

3.3 Correlating Permutations

After the survey was developed, Lurgio introduced the children to permutations, and asked them to list all possible permutations of yes-and-no answers to 4 questions.

Sample student work is shown in Figure 1. Students were not told that there should be exactly 16 unique permutations; many students generated more than 16 permutations, thus necessarily having duplicates. Also, the students did not appear to use a systematic process (such as counting in binary) for generating the permutations. It was hard for them to know when they were "done."

After giving the students a chance to work on their own, Lurgio generated a reference permutation chart for use by the whole class (also shown in Figure 2, left photo). As with the student's work, Lurgio's chart is idiosyncratic in its lack of an evident algorithmic method for generating the 16 yes/no combinations.

Lurgio then counted off each permutation in the classroom chart with a reference number from 1 to 16, as shown in small numbers in the chart (next

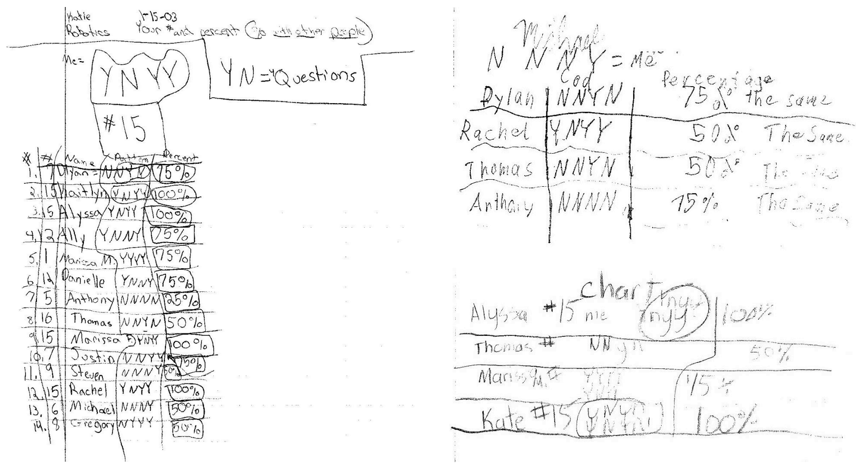

Fig. 3. Three students correlate themselves with others in the class. Each has written down her or his own string of Y or N answers to the 4 survey questions, and the answer-strings of other students. Based on counting the number of matching Y or Ns, the students have indicated match levels of 0, 25, 50, 75, or 100% between themselves and each of their peers.

to each permutation). Children in the class could then find their pattern of yes-no answers on the classroom chart, and determine their "magic number" by finding the corresponding ordinal number in Lurgio's chart. For example, the pattern "YYNY" (girl/left-handed/no pets/9 or younger) has magic number 9 in Lurgio's representation.

Next, Lurgio developed the idea of "percentage of match." If two people matched on all answers, they had 100% match. If they matched 3 of the 4 answers, they had 75% match, etc., to a 0% match for no matching answers.

Using this representation, Lurgio developed the chart shown on the right side of Figure 2, which correlates magic numbers to percentage-of-match. The chart uses on color-coded graph links to indicate percent of match between various pairs of magic numbers. For example, the link between magic number 16 (answer NNYN) and 6 (answer NNNY) is drawn in green, indicating a 50% match between these two individuals. (The chart itself only includes magic numbers of actual students and staff in the classroom, so all links are not drawn.)

Now students could personalize and contextualize the combinatorics. Instead of thinking about abstract combinations, they could formulate their own pattern of yes/no answers, and compare with it with the patterns of other students.

Students interacted throughout the classroom, exchanging their answers and resulting reference numbers. As shown in Figure 3, students then correlated their answers with those of their peers, calculating a "percentage of match" amount. This was done by counting the number of matching answers between themselves and their peers (they did not need to use the linked-graph representation). If there was one match, then they had a 25% correlation. Two matches yielded 50%; three, 75%; and all four matching was 100%.

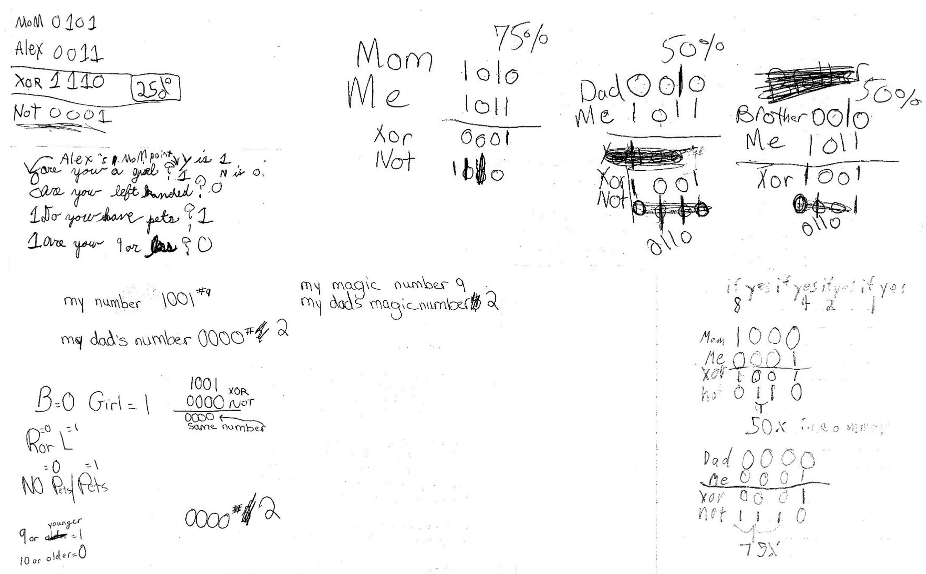

Fig. 4. The work of four children from take-home assignment in binary matching themselves with parents and siblings.

3.4 A Binary Representation and Boolean Algebra

After these activities had taken place, Martin joined the classroom and introduced a modified representation based on binary numbers. Martin replaced a Yes answer with the binary digit 1 and a No answer with a 0, and demonstrated binary place value for calculating the magic number.

Question 1 ("are you a girl?") was then the high bit of the representation, so it had a decimal value of 8. Question 2 ("are you left-handed?") was worth 4, etc. Students then recalculated their magic number using the binary representation.

The particular choice of the girl/boy question as the high bit led to a result where all of the girls in the classroom had magic numbers between 8 and 15, while boys had magic numbers between 0 and 7. A couple of the boys were somewhat disappointed that they had magic numbers of 0. They felt a little better when they learned that they shared with magic number with Martin.

Students were then shown how to calculate match levels by using the Boolean exclusive-or (XOR) function, which produces a 1 if either (but not both) of its inputs are 1. The XOR operation was followed by the Boolean NOT, to convert the non-match 1s into 0s (and vice-versa). This was demonstrated in class using various pairs of the students.

The fact that the Boolean procedures were being done on students' own data was of great significance. The 1s and 0s were not abstract values, but represented individual children and their peers. So students were quite concerned with understanding what was being done with the numbers and how their magic number became assigned.

After this in-class session, Lurgio assigned a homework exercise in which students were to perform the XOR and NOT operation to compare themselves with their parents and siblings. Sample results from this homework are shown in Figure 4. Some students were able to perform the XOR and NOT operation, while others were able to get the correct answer (percentage of match) simply by counting matching 1s and 0s as they had done with Ys and Ns.

3.5 The Technology

For the Robotic Jewelry project, we introduced robotics technology based on Martin's prior work [5]. Students in the classroom were each given their own Handy Cricket [4], which would act as the "brain" or controller for their necklace.

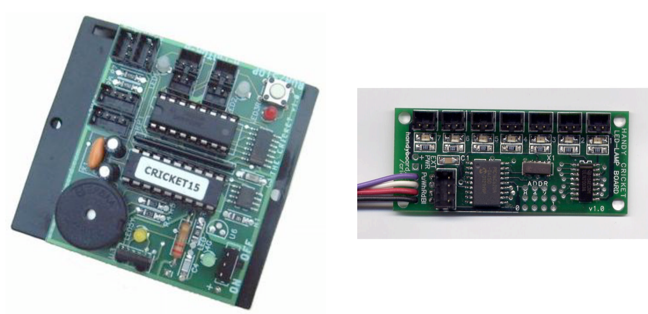

Fig. 5. Handy Cricket (left) and Lamp Board (right)

The Handy Cricket (Figure 5, left) is a hand-held, battery-powered embedded controller specifically designed for educational use. It is programmed by students using the Logo language, and it can interface with various devices like sensors and motors. For the Jewelry project, we used Velcro straps to attach the Handy Cricket to students' wrists, so they wore them like an oversized wristwatch.

The Cricket also has a built-in, infrared communications feature. We used this to let the children's necklaces "talk" to one other (i.e., exchanging their wearers' magic numbers). To enable the communication, students had to hold their wrists toward one other, so their Crickets could see each other.

Finally, we designed a lamp controller accessory board for the Cricket (Figure 5, right). This board was capable of driving 7 lamps; commands for controlling the lamp outputs are described shortly. The Lamp Board would be used to create the flashing patterns that would distinguish the different percentages of match.

Fig. 6. Some of the materials used to build the necklaces—commercial hoop earrings (left) and Cumberlandite rocks (center); Wearing his creation (right).

3.6 Necklace Design

As the electronic/computational materials were being procured and developed, Lurgio led the conceptual design for students' necklaces. A Cricket would primarily power each necklace, but each necklace would have an overall decorative design that was created individually by each student. All necklaces would have a string of flashing lamps woven into their overall design, but would have a separate V-shaped chevron of lamps that were plugged into the Lamp Board. This chevron would be used to display different flash patterns depending on match levels when two children met.

Lurgio brought a variety of materials into the classroom for students to be used in creating their necklaces, including commercial hoop earrings, LEGO elements, and Cumberlandite, the state rock of Rhode Island (see Figure 6).

3.7 Children's Programming Activities

We then introduced the children to programming activities with the Handy Cricket and Lamp Board. Software commands were available for turning on and off individual lamps (e.g., "set 4" and "clear 4"). Also, there were commands to rotate the whole pattern of the display around to the left or the right ("rotleft" and "rotright"). For example, if lamp 1 were illuminated and rotright were executed, the display wraps around, and lamp 7 would turn on.

We discussed the programming a whole group, and then over a series of sessions, each of the students in the class (working in pairs) had time in front of the computer, entering commands to turn the lights of their own necklace on and off.

These were playful and exploratory, as we encouraged the students to try different things and see what happened. Near the computers, we wrote commands on the classroom blackboard to get them started; e.g.:

```
set 1 set 3
repeat 100 [rotleft wait 1]
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The students tried things like increasing the repeat count, to get it to run longer, and reducing the wait argument to 0, to get it to run faster.

Later, we began a more focused discussion about what sort of flash patterns they would like to create for the necklaces.

Several ideas emerged from the discussion. We introduced a flash pattern we called "Curtain," which had the lights come in from the edges, in a series of steps, as if the lights were a curtain opening and closing. The children proposed a pattern called "Chicken" and then its complement "Reverse Chicken."

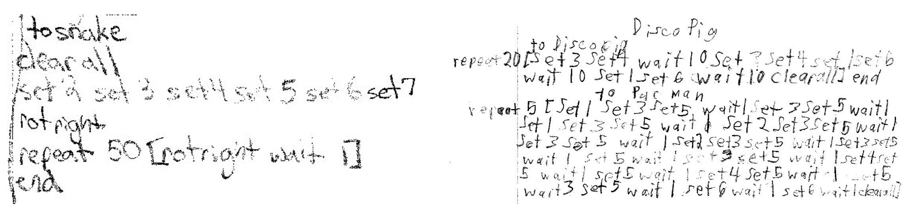

Fig. 7. Code written by students to create different flash patterns. "snake" displays a light-chase pattern; "disco pig" and "pacman" are hard to describe in words.

We created worksheets for students to develop their own designs, along with the programs to accomplish them. Then, when students went back to the computers, they had specific projects to work on. One pair of students reversed the Curtain display, creating what became called "Explosion." Experimentation with the rotate command led to a display called "Snake" (see Figure 7, left).

One of the students took a particular affinity to this activity and filled his notebook with a variety of designs, with names like "Dynamite" (like Explosion, but with a fuse) and "Disco Pig" (no explanation). Two examples of his work are shown in Figure 7, on the right.

In a whole-class discussion, we assigned displays to different match levels. The children's consensus was Explosion = 25%, Curtain = 50%, Snake = 75%, and All Blinking = 100%. (Chicken, Reverse Chicken, and the Disco Pig did not make the cut.)

In programming their own necklace, the abstract and "academic" knowledge of formal representation (that is, school mathematics) crossed over into the dimension of practical reality. In other words, the classroom discussion and writing on the board became something wholly other than a theoretical discussion. The abstract/formal knowledge could actually be used to do something—to cause the lights on my own necklace to flash into a particular way.

This act, of programming one's own necklace, was the transformative one. Students realized that the mathematical conversations were not just adults talking, but were in fact actionable knowledge that they personally had an interest in, because they could use it to make something they cared about.

3.8 Developing the Control Program

Coffey and Martin took the lead in developing the master control program for the necklaces. The program caused each necklace to: (1) transmit its own magic number; (2) receive a magic number from another necklace; (3) perform the XOR-NOT operation to determine degree of match; (4) select and play the appropriate flash pattern based on the match; and then (5) loop and do it all over again.

Coffey prepared a worksheet explaining the master program to the students. It was about 20 lines of code (not including the flash pattern subroutines). A subgroup of students took charge of understanding how to load the program into the necklaces and then program each necklace with its wearer's magic number.

3.9 Public Demonstrations

The class presented its work in two significant public events: the spring Botfest exhibition at the University of Massachusetts Lowell, and the spring Robotic Park exhibition organized by the Rhode Island School of the Future consortium.

Adult visitors would be drawn in by the cheerful and gregarious group of youngsters, each wearing a matching T-shirt and similar-looking glittery necklaces. They would see the electronics and blinking lights, and initially assume that the children had merely built a pleasant flashing display.

But then a child would grab a visitor's hand and bring him or her to a programming station. The visitor would be shown the 4 questions, and a child would convert the answers into the adult's magic number. This number would be programmed into a spare necklace on the spot. The visitor was lent the necklace and sent off to mingle with other children.

Then one of several students would perform a parlor trick. The child would flash necklaces with the visitor, decipher the flash pattern (to the casual observer, "Explosion" and "Curtain" were all but indistinguishable, but not to the children) and then, based on the child's knowledge of her own answers, and her observations of the adult's gender *infer what the adult's answers to the have-pets? and left-handed?* question must be. All of the mathematics required to do this were fully internalized by several of the children.

Many adults who took the time to partake of the full experience left very impressed.

4 Discussion

The Robotic Jewelry project wove together so many components of learning, they are hard to single out or treat separately. The whole project was an improvision, performed in concert with a willing and interested group of students who became essential participants. We literally did not know exactly what would happen, but with good judgment and mutual trust expected that we would converge with a successful design (which we did).

For many of the children, the transition of mathematics from an on-paper exercise to the in-the-world, wearable "robotic jewelry" was an unprecedented experience. To expect children to become excited about mathematics in the way that many practicing engineers and scientists are, this kind of experience has to become commonplace rather than exceptional.

We hope this project might provide inspiration to others who might attempt their own version of collaborating with their students in design projects. The children really do know when you're putting your faith in them.

Acknowledgments

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