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Engineering Design of Cars and Gadgets in K-5 as Vehicle for Integrating Math, Science and Literacy

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ABSTRACT

In spite of numerous calls for action, e.g., Executive Office of the President (2010), there have been few efforts nationally to promote engineering education in the elementary grades. Of these, hardly any have targeted underrepresented populations (National Academy of Engineering, 2009, p. 74). The collaboration described in this paper is a significant exception, which could provide important lessons for those seeking to broaden the reach and scope of K-5 engineering education. We will argue for an interdisciplinary approach, which integrates engineering, math, science, literacy and art, and that engages a school and a university as equal partners. Neither of these components has been prominent in the literature on K-12 engineering education.

Keywords: Elementary education, school-university partnership

BACKGROUND

This paper will synthesize and draw lessons from the experiences of a curriculum and professional development project, which has been funded by the National Science Foundation through the Discovery Research K-12 program The goals of the project are to develop and support the use of materials that promote integration of engineering with science, math, literacy and art in the elementary grades. Children engage in designing, making and testing their own devices. These include cardboard mechanisms that animate stories; paper pop-ups; gravity-, elastic- and electric-powered cars, and gadgets with hidden switches that produce light, sound and/or motion when opened or closed (City Technology, n.d.). Through these activities, students develop facility with materials, plus an understanding of systems, models, design, constraints, redesign and troubleshooting, which are core concepts in engineering education (National Academy of Engineering, 2009; National Research Council, 2012). Physics concepts include motion, force and energy. Writing is an essential component of the project, and of science education generally (Worth, *et al*, 2009).

There are eight curriculum units in two sets of four each, under the headings of Force and Motion and Energy Systems. Each set consists of one unit each for grades K-1 and 2-3, and two units for 4-5. Classroom sets for the units cost between $100 and $300 apiece, and many of the materials can be acquired by recycling instead of purchase. As part of the Energy Systems Curriculum, students create gravity-powered cars in the K-1 unit Invent-a-Wheel, wind-up vehicles in the 2nd-3rd grade unit Fantastic Elastic, and electric cars in 4th and 5th grades in the EnerJeeps unit. In the course of this work students write their own equipment lists, instruction manuals, troubleshooting guides and analyses of how their devices work. The analysis leads directly to basic concepts of physical science. When students operate their wind-ups, for example, they experience the use of their own power to store energy in a rubber band, and witness its release as kinetic energy when they let it go.

Each unit has been through three development phases:

- Research and development by a small group of teachers in collaboration with university faculty, who tried ideas out in their own classrooms, made revisions and led professional development sessions for other teachers;
- Pilot tests in local public schools, supported by frequent visits by project staff;
- Field tests in Washington, DC, Los Angeles and Northern Minnesota.

The pilot and field tests have taken place in predominantly low-income schools, both rural and urban, and have included Special Education and English Language Learners as well as general education students.

The primary site for pilot-testing is Public School 5, located in a low-income community of a large metropolitan center. According to the most recent data, 82% of the student population is African American, 15% is Latino and 89% are eligible for free lunch. The teaching and support staff are overwhelmingly of African American or Afro-Caribbean backgrounds. Two of the co-authors played major roles in the pilot testing of the curriculum materials at PS 5: the Librarian and the Science Teacher. Both implemented project curriculum units with multiple classes at different grade levels. The third co-author is an engineering faculty member at a nearby public urban university, and Project Director of the curriculum and professional development effort.

Before beginning the pilot tests, the R&D group of five teachers spent two years developing curriculum ideas in collaboration with project staff. The R&D teachers then tested these ideas with their own students, wrote or modified curriculum and provided content for the project web site. Curriculum elements, including an entire unit, were sometimes rejected as a result of these tests. Eventually, draft curriculum documents were written, and became the basis for two Summer Institutes, each of which was designed to prepare for pilot tests the following Fall. These sessions were planned and led by the R&D teachers as well as the university faculty.

During the pilot tests, the university partners visited the school frequently, observing students at work, making suggestions and occasionally teaching lessons themselves. The major purpose of these visits and tests was to collect data from teachers and students about how to improve the curriculum. At the end of the pilot tests, project staff met with all the pilot-test teachers in grade-level groups to determine what had worked, what hadn't and how teachers had modified the curriculum units to meet the needs of their own students. This information has led to further changes in the curriculum. A similar process took place during the field tests.

Nine pilot-test teachers became so involved in thinking about and modifying the curriculum that they subsequently joined the R&D teacher group, which now consists of 11 teachers, two of whom are co-authors of this paper. In addition to their roles in developing curriculum, the R&D teachers have gradually formed into a professional learning community, collaborating with one another in writing papers, presenting at conferences, creating videos for the project web site and providing professional development at the field test sites.

Development of assessment instruments for PSCA has likewise been a collaborative effort between teachers and project staff. Learning objectives and rubrics have been developed to align with the new Science Education Framework (National Research Council, 2011) and the Common Core Standards for ELA. Preliminary data based on these assessments is presented under **Student Outcomes**, below.

INVENT-A-WHEEL

One of the co-Authors is the Library Media Specialist at Public School 5. She collaborated with two Kindergarten classes to support the Invent–a Wheel unit, in which each student designed a car that would roll down a ramp. This unit develops science concepts such as *gravity, force, energy* and *friction*. The goals were for students to synthesize their experiences using grade- and content-appropriate language, to verbalize their predictions, conclusions, problems, modifications and solutions, and show a clear understanding of the relevant science concepts. A culmination of this unit was for students to create "How-to books," describing how they had made their cars.

The first step was to have students move small objects that cannot roll, such as books, blocks, and pieces of cardboard. With their classroom teachers, they discussed the different ways to make objects move, such as *pushing*, *pulling*, *blowing* or *moving* objects using sticks or pencils (see Figure 1). Students then were given large sheets of cardboard to see if these could help or hinder the movements of the smaller object. They used their inquiry skills to figure out how to get objects to move using this cardboard sheet as a *ramp*.

The next step was for students to explore slides in the playground. This would allow students to make connections and comparisons between the outdoor slides and the ramps they had used in the classroom. Students experimented with how objects would go down the slide, using different surfaces, objects and heights. They explored a variety of things that might help or hinder how things slide (see Figure 2).

Figure 1. Blowing on a block.

Figure 2. Testing objects on a slide.

Students were then introduced to the concept of a *sled* and its purpose. Students listened to the story Uncle Wiggily and the Sleds by Howard Garis. Students then made ramps using large cardboard sheets, which mimicked the slides. They used small cardboard rectangles as sleds. By now students had figured out how to use the ramp to make the sled go down (see Figures 3 & 4).

Teachers had begun to introduce vocabulary words such as *gravity* and *force*. Teachers also introduced inquiry concepts, such as what it means to do an *experiment*, make *predictions* and *test* their predictions. At this point students were given their first activity sheet, where they used color coded marks to indicate their predictions of the height of the ramp that would allow the sled to go down. Then they listed what they had noticed: were their predictions correct?

Up to this point, students had experimented only with ramps that had smooth surfaces. Now students began to explore different *surfaces* and *textures*. Teachers provided samples of materials with different textures, such as aluminum foil, felt, sand paper, and crumpled wax paper. Students felt each one and developed descriptive vocabulary to help identify their textures. Using words like *hard*, *soft*, *rough*, *smooth*, *crinkly*, *scratchy*, etc., students described how these surfaces could help or hinder how the sled would move down the ramp. The word *friction* was introduced to describe how things that "want" to move might get stuck instead. Using another activity sheet, students logged:

- The different kinds of surfaces,
- Their predictions of how far the sled would slide (in inches),
- What actually happened (see Figures 5 and 6), and
- How high they think the ramp would need to be for the sled to move down each type of surface.

At this point students could distinguish which ramps would allow the sled to slide and which ones wouldn't. They began to think about how they could re-design their sleds so that they could

Figure 3. Will it go down the ramp?

Figure 4. … not unless you lift it up!

Figure 5. Testing felt, sandpaper and…

Figure 6. … aluminum foil.

move on all the surfaces. Students used weights, paper plates, spoons, and washers to attach to their sleds so that they could find new ways to get them to move (see Figures 7 and 8). Vocabulary words such as *design*, *redesign* and *troubleshooting* were introduced. Students were given time to experiment with different surfaces and materials. They discovered that redesigning their sleds could reduce *friction*, allowing the sleds to move (see Figure 9).

They recorded their designs and explained what had happened (see Figure 10). Students were given the task of redesigning their sleds again. This time they were introduced to materials that could further reduce friction so that the sleds could move more freely. Students tried placing skewers, straws, stirrers, pencils or crayons under a sled to allow it to roll down (see Figure 11). After experimenting with different designs students were led in a discussion about the methods they had used. They talked about which ones had worked and which ones hadn't. The vocabulary words *roll* and *roller* were introduced. Teachers and students discovered that when rollers were added, they could help reduce friction so that the sleds could move down the ramps more freely. Students used additional activity sheets to chart their own designs and explanations of what had happened.

Figure 7. Looking for materials.

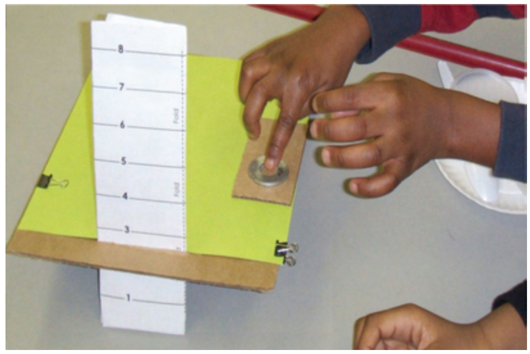


Figure 8. Adding weight to a sled.

Figure 9. Testing a redesigned sled.

At this point students could explain features of their sled/ramp re-design and could use appropriate vocabulary to explain what had helped to improve the performance of their sleds. They could articulate improvements they had made to their sleds and could create grade-appropriate graphics listing materials they had used and indicating how they fit things together to reduce friction on the sleds.

Teachers now began to lead discussions about the rollers. The teacher elicited information about the positive and negative effects of using the rollers.

- they help the sled go down, but
- the rollers don't stay on the sleds, and
- they may roll in different directions once they hit the bottom of the ramp.

Figure 10. Recording sled data.

Figure 11. Using rollers.

Students were given time to try to fix these problems. After another brief discussion of possible solutions, students were introduced to the plastic wheels. Teachers asked students key questions as to:

- The purpose of this object,
- What it's called, and
- How it can aid in the design of a car.

The words *wheel*, *axle* and *stop* were introduced. Students were then given plastic wheels, skewers, beads, clips, and clay to aid in the redesign of their sleds. The sled with wheels was renamed a *car*. Students planned and built models of their cars using familiar materials, processes, and tools (see Figure 12). They spent time experimenting with these materials to see if they could get the car to roll down the ramp. They modified their cars to improve their performance. Students were then given time to identify and record the names of the parts they were using and to describe their functions.

Students were partnered off and then given time to compare their cars by rolling them down ramps to see what happened (see Figures 14 and 15). A class discussion took place about:

Figure 12. Fitting an axle onto a wheel.

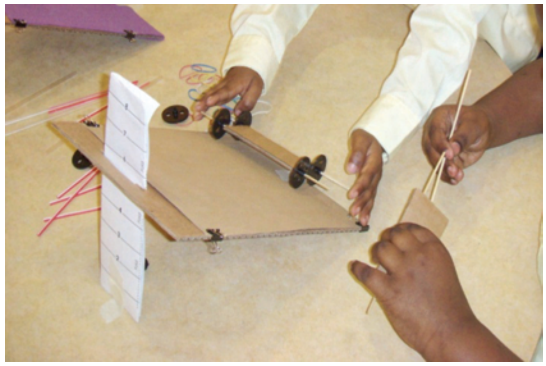


Figure 13. Testing a car.

- On what surfaces did the cars roll down the fastest?
- Did cars roll along *straight* or *curved paths*?
- How *far* did they roll,
- Did the cars stay together or did they fall apart?

In their science notebooks, students listed questions with their partners. They recorded how their car tested against their partner's and any other questions that developed.

Now students were ready to start preparing to make their How-to Books. How they would be able to remember the steps in making their cars? Teachers guided the lesson by eliciting that they could use drawings to help them remember the steps in making a car. Students were given worksheets to draw their cars (See Figure 16). Teachers presented the concepts of *labeling* and of looking at an object from different *viewpoints,* by constructing drawings showing the same object from different viewpoints, both with and without the use of labels. A class chart was developed based on the students' ideas. They then made a second set of drawings using labels and showing the car from the *top*, *bottom* and *side* views (see Figure 17).

By now students were able to compare how things look from different viewpoints, and could represent different views of the same object. They were now ready to make their How-to Books. Teachers used the example of construction sets like Lego™. When you are building something, how would you know what to do? Students remembered that there is an instruction sheet that tells you what to do. Teachers discussed how there are *steps* to follow when making something. They will be creating How-to Books listing the steps they had followed in making their own cars. After reviewing the steps that the students had followed, each student used a worksheet to write a How-to Book showing how he or she had made a car (see Figure 18). Students were then given time to share their How-to books with each other.

Figure 14. Comparing how cars go down...

Figure 15. ...one made it all the way!

Next, students had the opportunity to redesign their cars so that they would work better or look better. Teachers distributed art supplies and craft materials and students were able to enhance the features of their cars (see Figure 19). Students were then given time to write about their redesigned cars. As a culminating event, kindergarten classes had a Car Show in the Library (see Figure 20). They were given time to race their cars against students from the other Kindergarten class. Finally teachers created a Car Museum in their classrooms where visitors could view the cars and learn about how they had been made.

Through this process students were able to meet and exceed the performance indicators for Kindergarten set forth in the New York State English Language Arts Core Curriculum (New York State Education Department, 2011). Students were able to draw and/or write to express and share what they had learned about their topic. They were able to use organizational patterns such as time-order to list the steps in making their cars. Students used appropriate vocabulary words and language

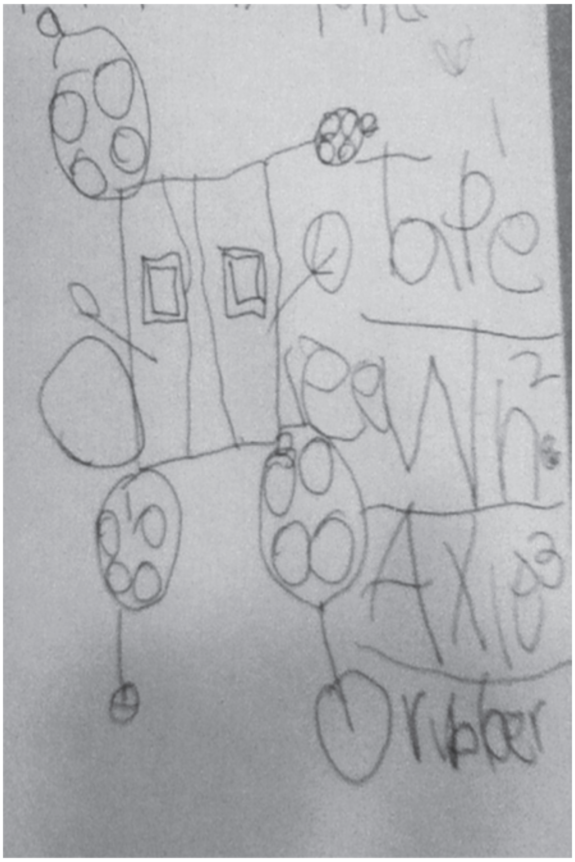


Figure 16. First drawing of a car.

to express in writing the design and construction of their cars. They also wrote in their journals to express their feelings and experiences throughout this design process.

ENERJEEPS

Another co-Author is the Science Cluster teacher at Public School 5. She has implemented Physical Science Comes Alive! units with second and fourth grade students entitled MechAnimations and Enerjeeps, respectively. These were the catalysts for many independent inquiries in her classroom. Most recently, she collaborated with a fourth-grade teacher in implementing the EnerJeeps curriculum unit. Performance objectives for the students at the end of each project have been twofold:

- to enable students to become independent thinkers and problem solvers, and

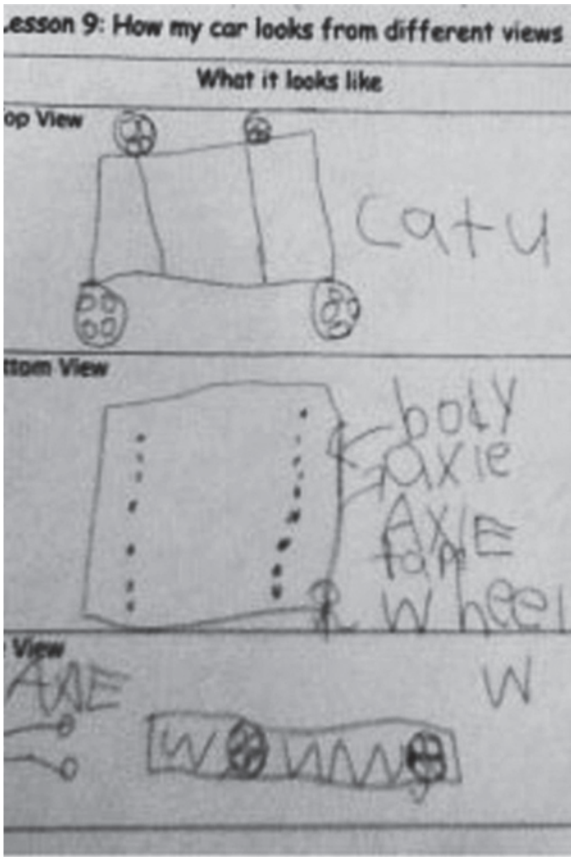


Figure 17. What it looks like from the top, bottom and side.

- to improve analytical skills.

To accomplish these goals, the teacher's role in the classroom had to become that of a facilitator and not an instructor. Students had to be given the freedom and the time to explore and find new ways to solve their issues.

The EnerJeeps unit starts by having students work with motors, make switches, explore circuits, and make cars that roll. Students then create propeller-driven and direct-drive cars, which they present to an audience at the conclusion of the unit. The Penguin Race™ Toy is used initially to illustrate concepts of electricity, such as *circuit*, *current*, *voltage*, *source* and *load*. The toy features plastic penguins that roll down a descending racetrack, and are lifted back to the top by a motorized stairway. Students are asked to think about:

- What travels around in a penguin circuit, and in an electric circuit?
- What is playing the role of the battery in the toy?

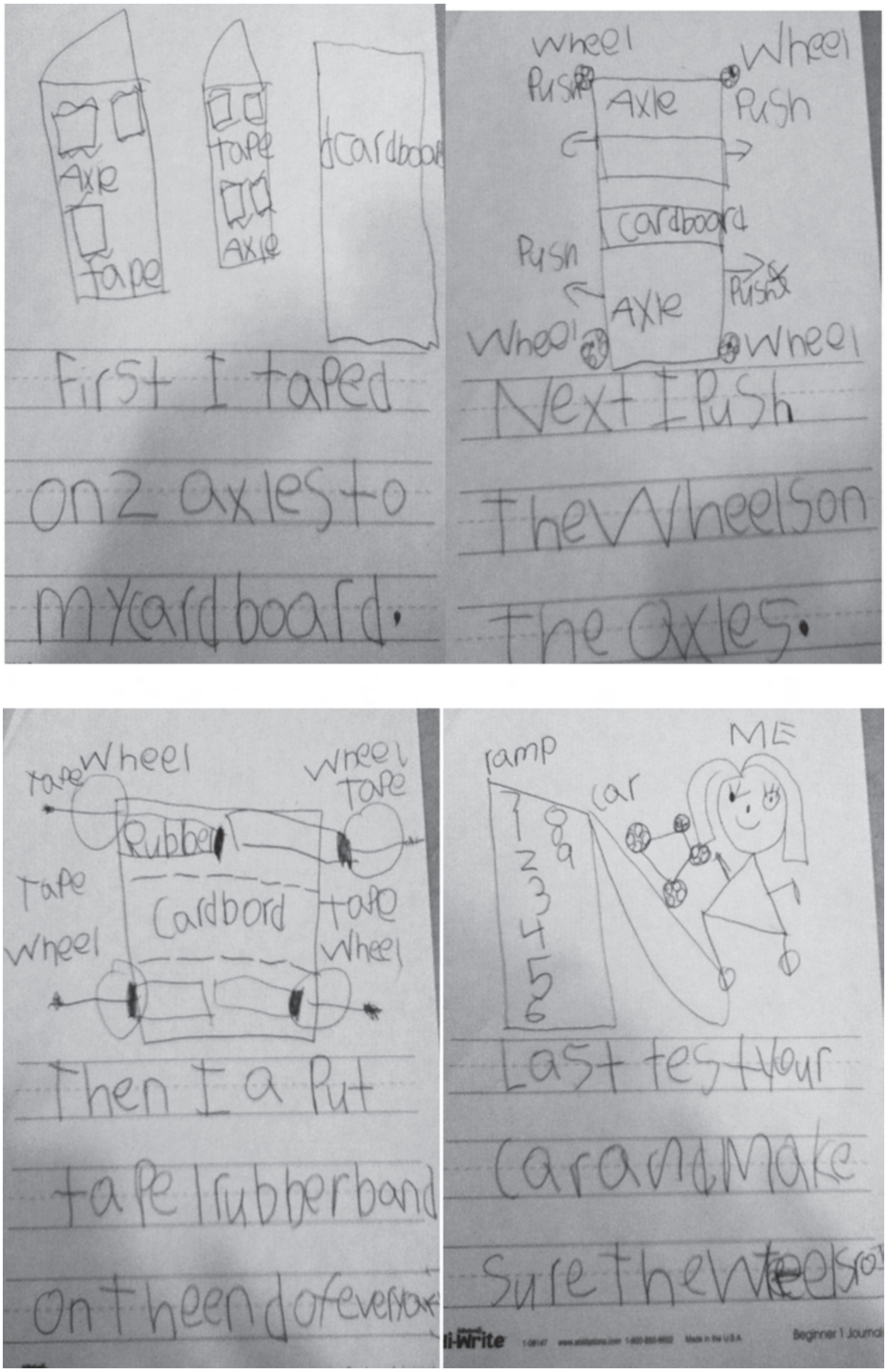
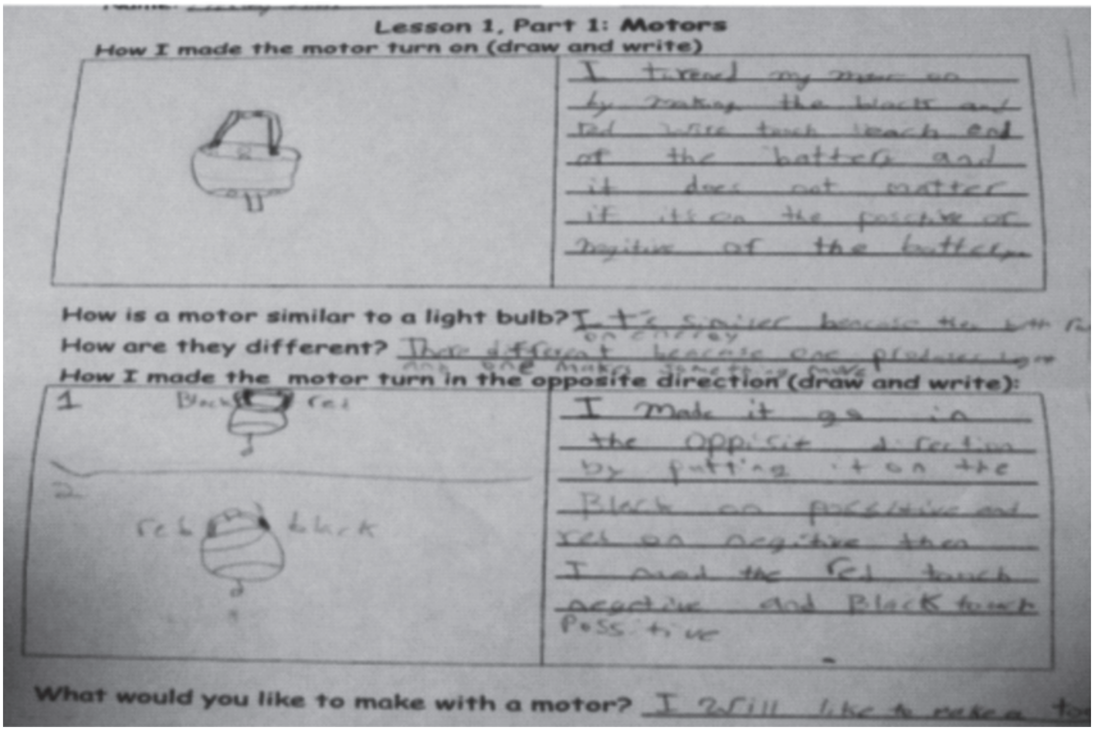


Figure 18. How-to" Book.

Figure 19. Customizing a car.

Figure 20. The Car Show.



Lesson 1, Part 1: Motors

How I made the motor turn on (draw and write)

I turned my motor on by making the black and red wire touch each end of the battery and it does not matter if it's on the positive or negative of the battery.

How is a motor similar to a light bulb?

How are they different?

How I made the motor turn in the opposite direction (draw and write):

I made it go in the opposite direction by putting it on the black on positive and red on negative then I made the red touch negative and black touch positive

What would you like to make with a motor?

Figure 21. A student's explanation of how to turn a motor on.

- Why does the racetrack need to be attached to both the top and bottom of the escalator?
- Why does the light bulb need to be attached to both sides of the battery?

Next, students were challenged to turn a motor on. Since they had already explored electricity concepts using batteries, bulbs and wires, they would now replace the bulb with a motor. Students were asked:

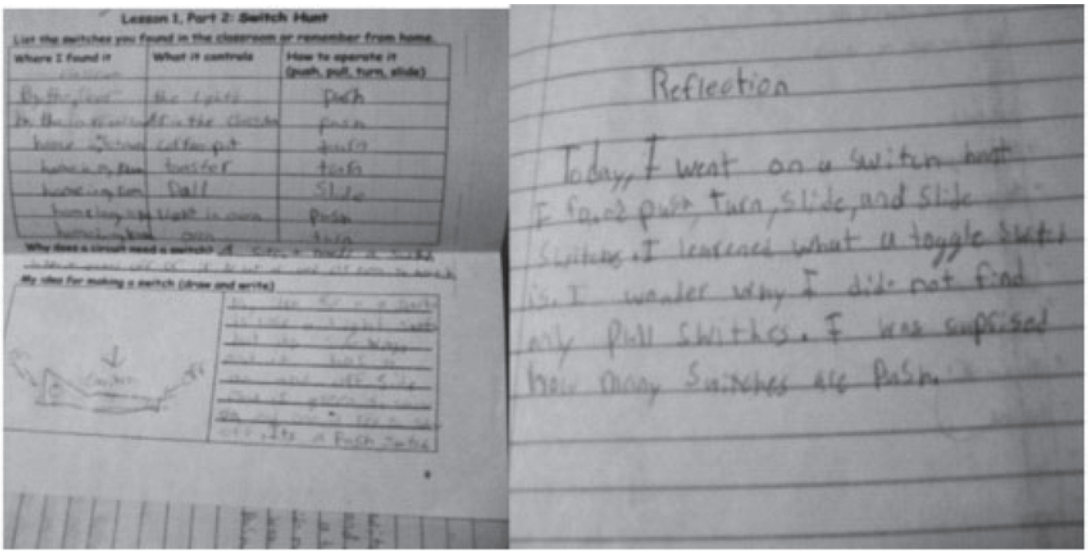


Figure 22. Students record where they found switches, what they control and how they work.

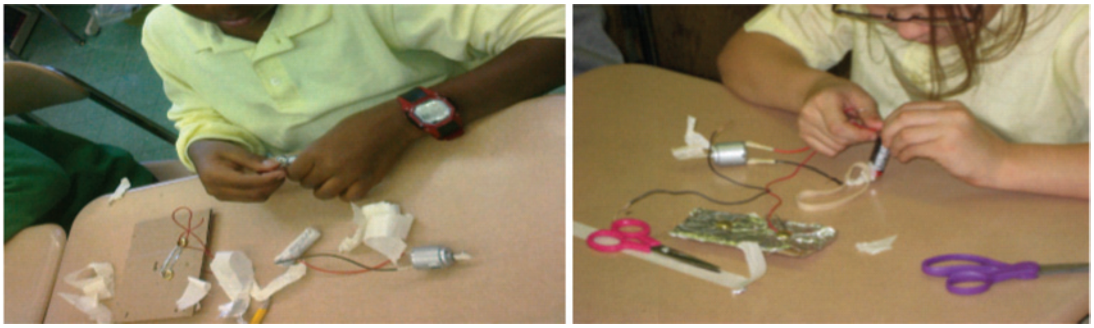
- What does a motor do?
- How will you be able to tell when the motor is running?

Then they made diagrams of their motors, and then wrote about how they got their motors to run. They tested their motors in one direction and then found a way to make them turn the opposite way (See Figure 21).

A discussion of switches followed. Students talked about what they had done to turn their motors on and off. They also described what a switch does and the advantages of using one rather than touching two wires together. This lead to a Switch Hunt: a scavenger hunt for switches at home. Students recorded where they found switches at home, what each one controls and how to operate it: push, pull, turn or slide. They then explored different ways for making a switch from common materials, and wrote plans for creating their own switches (see Figure 22).

Next students were allowed to make their own switches. Later, they designed and created as many types of switches as they could and used them in circuits to control their motors (see Figures 23 and 24).

In the next lesson, students attempted make cars that would roll easily when pushed or launched from a ramp. In a whole-class discussion, students looked at the parts necessary to make a car, how they would put them together and the parts that would and would not turn. Students recorded their ideas and began building their cars. They very quickly confronted issues of *friction*, and developed



Figures 23 and 24. Students control their motors with switches.

Figures 25 and 26. Students test their cars to make sure they roll.

means of reducing it. Students discussed the issues that came up, then worked on how to make their cars go straight (see Figures 25 and 26). At this point the words *axle, body* and *friction* were introduced.

The next challenge was for each student to make a car that is driven by a motor. Students were asked to think about a way that a motor could be used to make a car go. Students suggested attaching the motor to the wheel or having the motor connected to "something like in the front of an airplane." Later they discovered the word *propeller*. They worked on how to make a *direct-drive car*, which has a wheel attached directly to a motor. Students wrote a plan of action which they would use as a guide in making their cars (see Figure 27). After building their cars, they tested them for friction (see Figure 28) and then reflected on the activity as a whole (see Figure 29).

The concepts of *troubleshooting* and *redesigning* were then introduced. Troubleshooting was a way to find and solve issues that hindered their cars from rolling in a straight line. This issue could be due to the wheels touching the cardboard, or the motor being too tightly fastened to the wheel, or the two axles not being parallel. Students were expected to test their cars, identify the problems and develop methods for solving them. Because working independently and utilizing problem

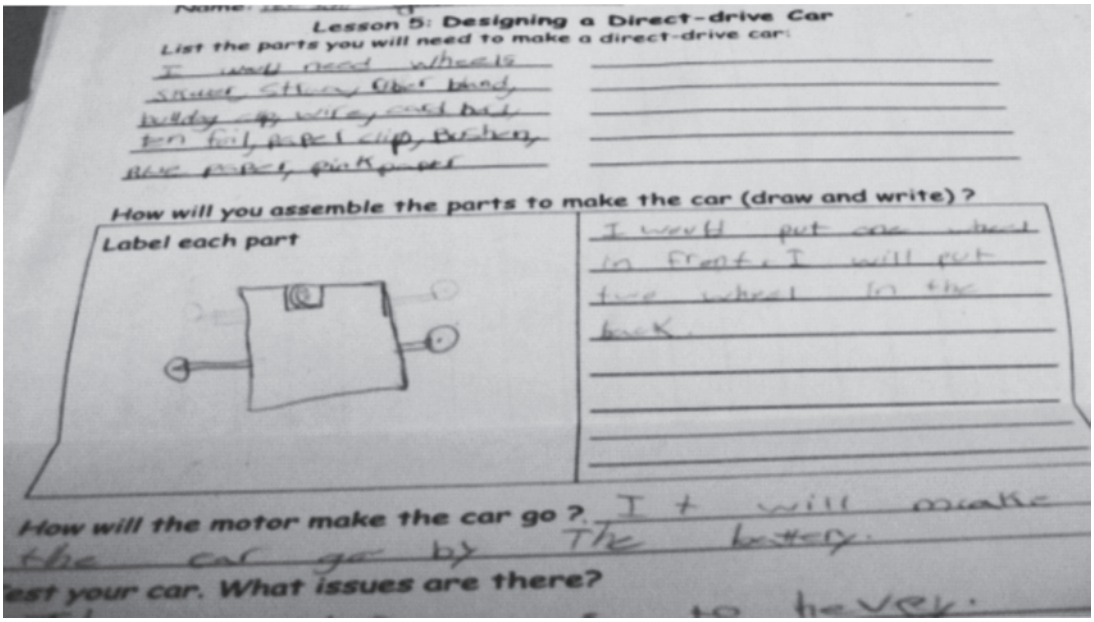

Lesson 5: Designing a Direct-drive Car
List the parts you will need to make a direct-drive car:
I will need wheels
skewer, straw, fiber board,
bulldog clip, wire, card box
tin foil, paper clip, bushing,
blue paper, pink paper
How will you assemble the parts to make the car (draw and write)?
Label each part
I won't put one wheel in front. I will put two wheel in the back.
How will the motor make the car go? It will make the car go by The battery.
Test your car. What issues are there?

Figure 27. How to make a direct-drive car.

solving skills can be a new concept for many students, the threshold for frustration can be reached very quickly. It is essential that the facilitator be aware of when students are close to their point of frustration, and be ready to help them to overcome their struggles by suggesting ways to look at things in a different way. They recorded their issues, the possible cause for each one and some solutions that might work (see Figure 30.)

One simple rule was strictly enforced: each student had to make some improvement to his or her project by the end of each session. The change could involve making a wheel roll that hadn't previously, improving the customization (see Figure 31) or anything else the student deemed relevant to the desired outcome. In fact, this practice had become such a part of the routine in the classroom that students would question each other at the end of the sessions about what improvements they had made that day. However, students were never told what to make or how to make it. This process has allowed the students to work independently to build their problem-solving skills as well as to become independent thinkers.

A major goal was to improve the students' analytical skills. The instinct to take a step back and think about a problem does not happen naturally for most students. This lack of analytic thinking can be attributed to the intense focus and preparation that goes into taking standardized tests; very little independence is built into a student's workday. There are very few opportunities for students

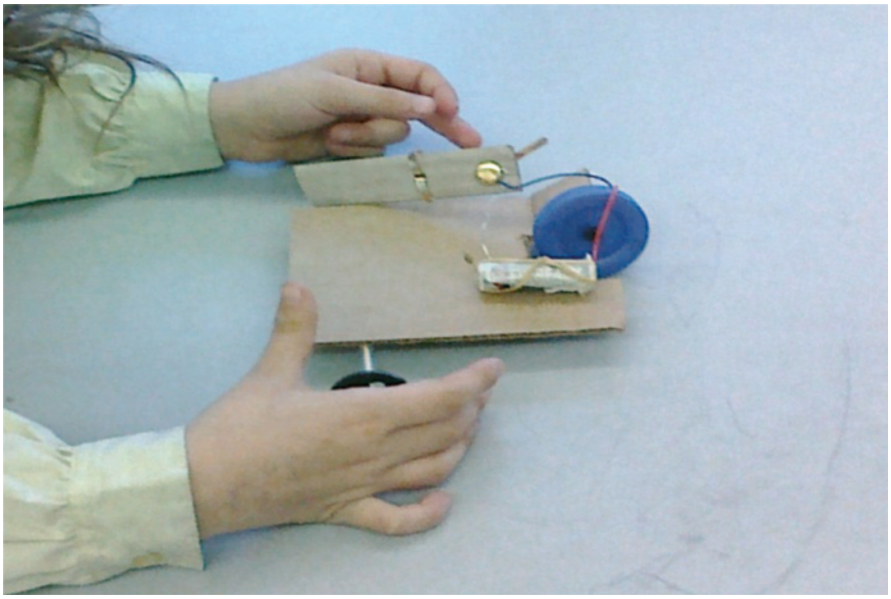
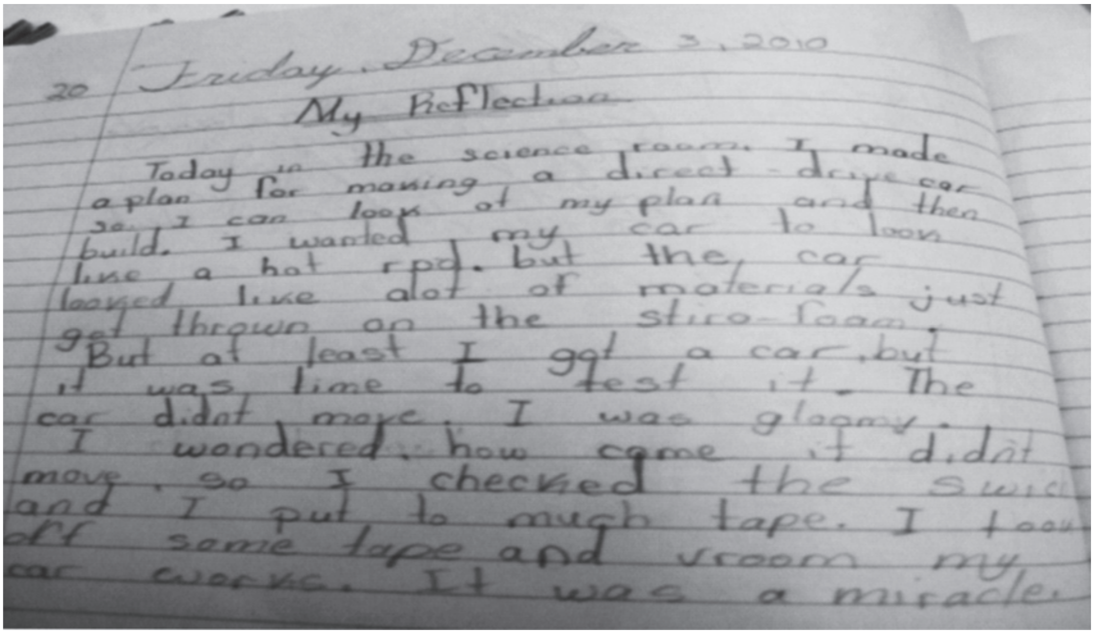


Figure 28. Testing a direct-drive car to make sure it can roll freely.

to analyze and come to a logical conclusion. Students had to be reminded to explore the reasons for the problems that arose, as a step towards solving them. One activity which allowed students to build their analytical skills was writing reflections in their journals. At the end of each session, students reflected on the day's activity. They were free to write about whatever they wanted in their journal, whether it was a "light bulb" instant, a moment of frustration or a discovery of a new way of doing something (see Figure 32).

Near the end of the unit, students had finally arrived at the point of customizing their cars. Not only could they add artistic flourishes, but also lights and horns, for which LEDs and buzzers were available. They first used a worksheet to record how many circuits they would need, how they would control each one and the type of battery and load in each circuit. Students listed the materials they thought they would need and drew diagrams of their first ideas (see Figure 33). After materials had been distributed, students were reminded that each circuit should have a switch, so it could be turned on and off.

Students then got ready for the Auto Show, where they would present their cars to an audience. They completed their cars, adding craft materials such as ribbons, pom-poms, feathers, cocktail umbrellas and craft sticks (see Figure 34). They tested them, did any troubleshooting and redesign that they thought was necessary, and then presented their cars to an audience of students and teachers. Each student showed his or her car and explained how he or she had

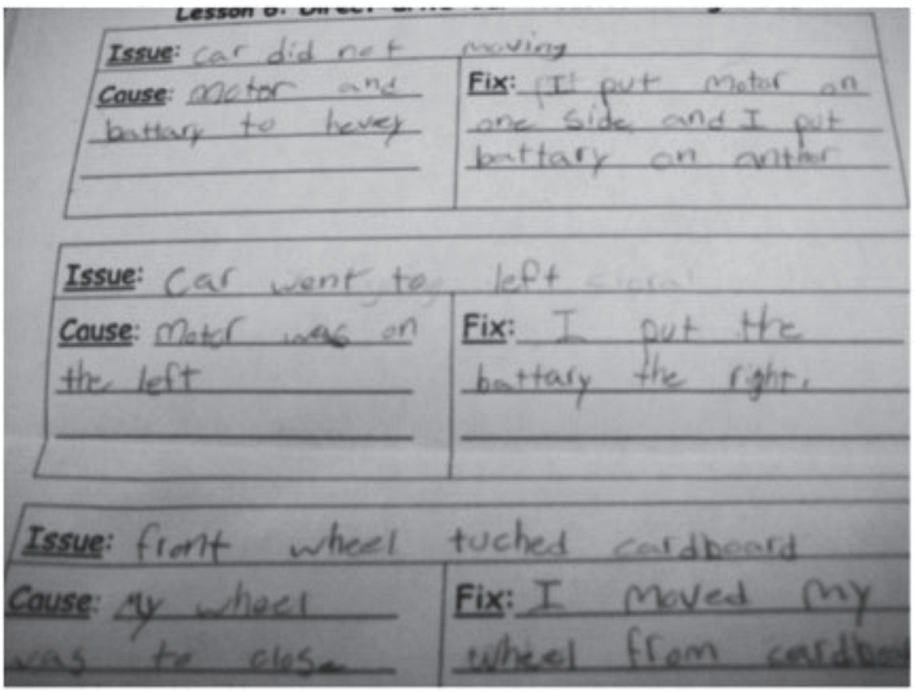


20 Friday December 3, 2010

My Reflection

Today in the science room. I made a plan for making a direct-drive car so I can look at my plan and then build. I wanted my car to look like a hot rod. but the car looked like alot of materials just got thrown on the stiro-foam. But at least I got a car, but it was time to test it. The car didnt move. I was gloomy. I wondered how come it didnt move, so I checked the swic and I put to much tape. I took off some tape and vroom my car works. It was a miracle.

Figure 29. Reflecting on the issues in making a direct-drive car.



Issue: car did not moving

Cause: motor and battary to hevey

Fix: I put motor on one side and I put battary on anther

Issue: Car went to left

Cause: Motor was on the left

Fix: I put the battary the right.

Issue: front wheel tuched cardboard

Cause: My wheel was to close

Fix: I moved my wheel from cardbo

Figure 30. Car issues and possible fixes.

Figure 31. Improving the customization of a car.

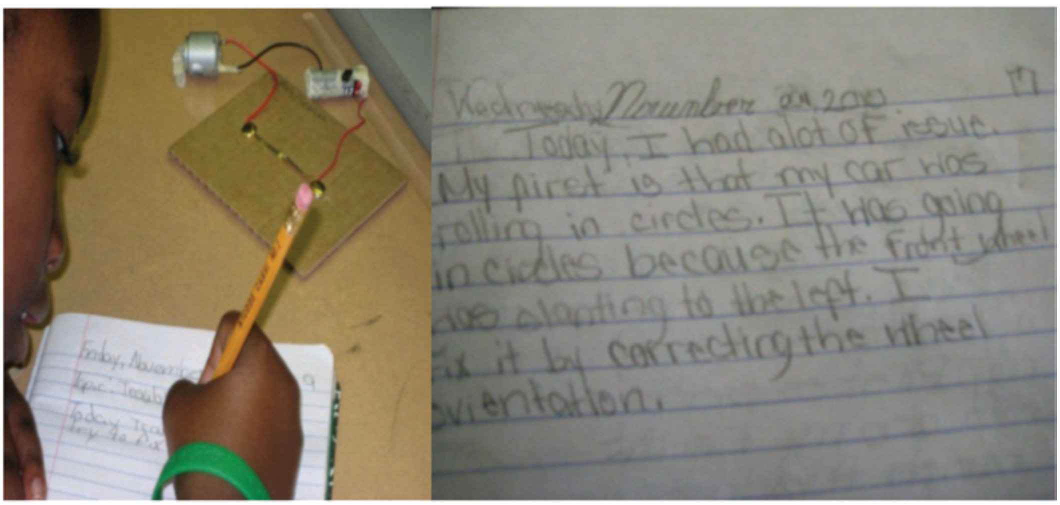


Figure 32. Reflecting on the day's activities.

made it. Audience members were then allowed to ask the students questions about their designs and ideas.

Engineering is a new concept for children in general, and is almost completely foreign to children in the inner cities. This experience allowed students to improve their problem solving and analytical skills through explorations, planning, trouble shooting, redesign and reflections.

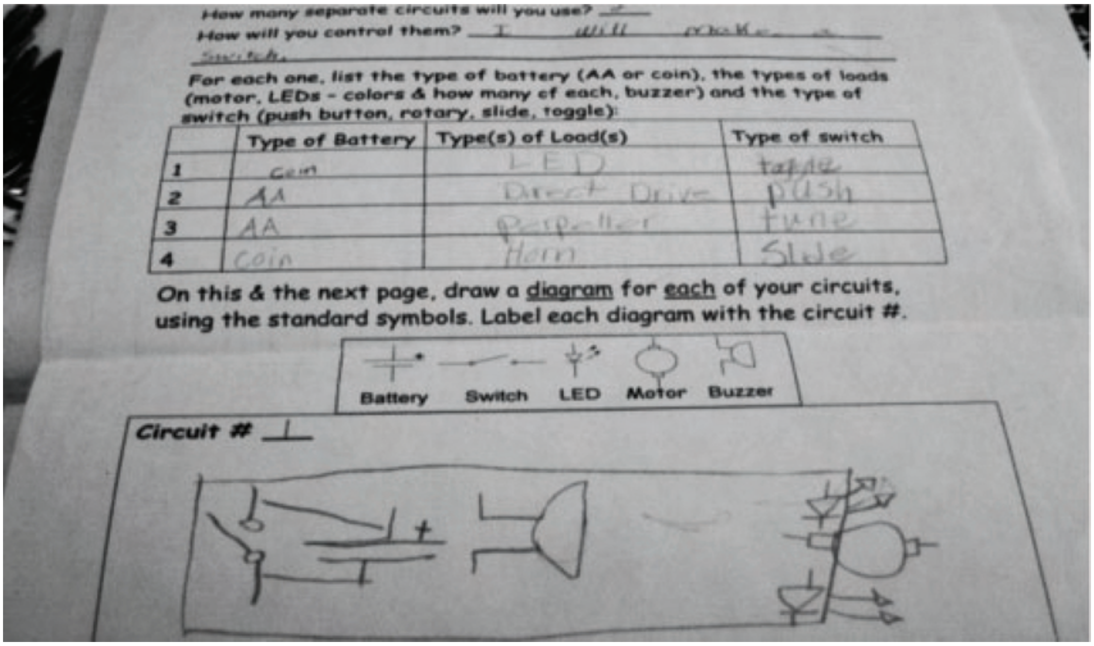


Figure 33. Designing the circuits for horns and lights.

STUDENT OUTCOMES

As mentioned above under **Background**, the project has developed a set of assessment materials to measure what students learn through the curriculum. Each lesson is aligned to a set of objectives. For each objective, there are rubrics that indicate the level of performance considered to be "below," "approaching," "proficient" or "advanced," relative to the expected outcome. While the program allows students to work at their own pace, and make their own discoveries, these assessments are intended to provide a clear picture of the students' understanding at each point.

Some assessments serve simply as a checklist or rubric so that teachers can know when particular concepts have been shared by a student. Teacher observation is critical in this work; there are many opportunities for students to be successful in this program: they draw diagrams, write plans and manuals, and construct switches and cars. By observing students and talking with them, a teacher can decide by what method a student is best able to communicate his or her learning. Some students may not be advanced in drawing a diagram or writing a manual but might be better at verbally communicating how to make a switch and the scientific knowledge that makes it work. Assessment materials have been pilot-tested for the first two lessons of EnerJeeps, and the outcomes are summarized below.

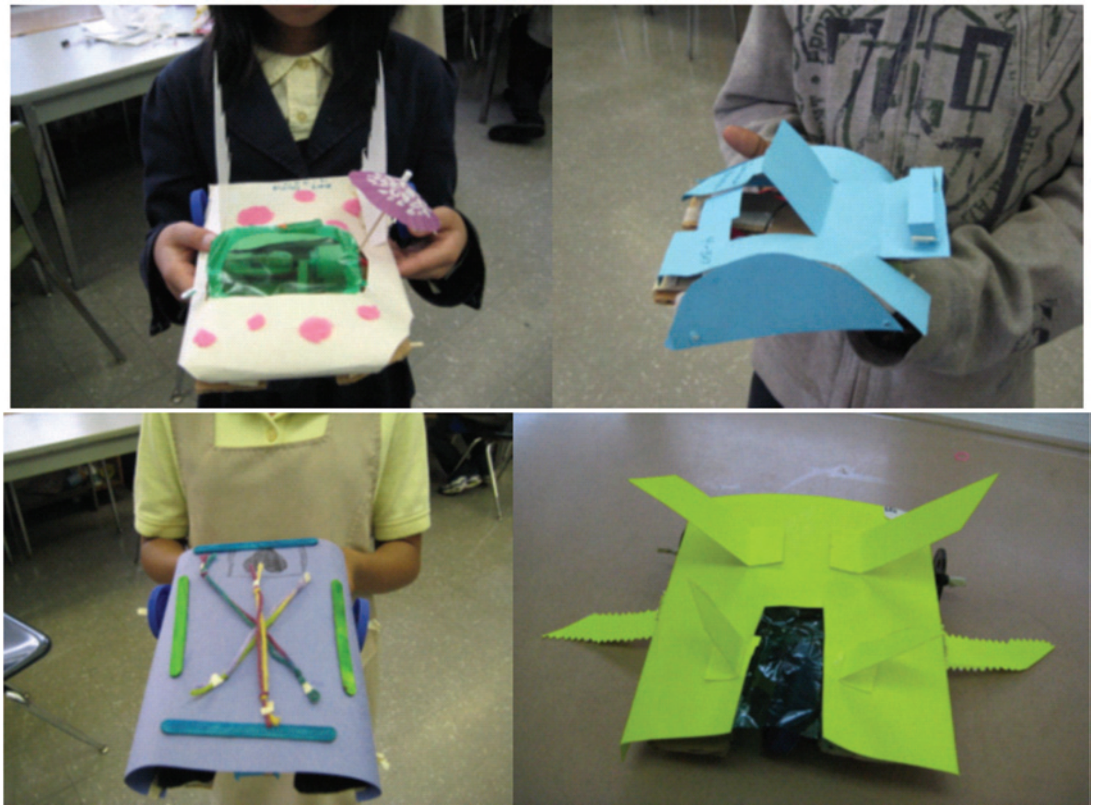


Figure 34. Presenting cars at the Auto show.

In the first lesson of EnerJeeps, for example, students were given time to explore using a motor and battery. The objective was for students to make a motor run and reverse its direction. Fifteen of twenty-five students were able to turn their motor on within ten minutes of exploration without any assistance from the teacher. Some were even able to assist other students who were having difficulty with the task. Five of the remaining students turned their motors on within fifteen minutes. By the end of the first forty-five minutes, ten students had recognized that their motors could spin in either direction and were able to reverse its direction. To see the direction, some students made cardboard propellers, which they attached to the shaft; while others held the shaft and watched the body of the motor spin.

In Lesson Two, "Make a Switch", students were expected to understand the need for a switch, design and construct a switch, and add it to a circuit. Students used a worksheet to look for and identify switches in their everyday environments and to describe the need for a switch in a circuit. Twenty of the twenty-five students brought back completed worksheets with examples of switches they had found in their homes and at school. One student wrote, "without a switch the television and other electronics would use up all of the energy". Although students recognized the need for a switch, many struggled with the concept of a complete circuit. Some work had to be done to build the understanding that a switch is a part of a circuit and that a switch opens and closes the path within a circuit.

CONCLUSION

This paper provides a preliminary look at a project that has engaged teachers and students in integrated K-5 engineering in low-income schools. The project now involves more than half of he teaching staff at two urban schools, one on each coast, and most of the few elementary teachers in some very small K-12 schools in a rural district with a large Native American population. One lesson of this project is that curriculum integration is much easier in an entire school, than on a classroom-by-classroom basis, because teachers can support one another. Because engineering is a foreign subject in nearly every elementary school in the US, introduction of engineering will be successful to the extent that it is integrated with science, math, literacy and art. However, as these experiences demonstrate, integration occurs naturally if the materials are explicitly designed to draw on other subject areas. Finally, curriculum and professional development design are complex processes that depend upon a wide range of expertise. University professors may be familiar with science and engineering principles, but are largely ignorant about what can and cannot happen in classrooms. Teachers may have less technical background than their university counterparts, but far more expertise about children, classrooms, schools and administrative issues. Close collaboration between university and K-12 professionals is therefore essential to any successful curriculum and professional development project.

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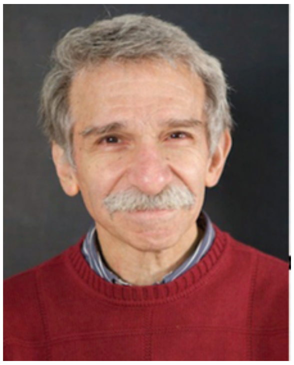

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