Making as the New Colored Pencil: Translating Elementary Curricula into Maker Activities

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ABSTRACT
We present Making activities designed and observed within the formal environment of elementary school classrooms. Using a collaborative curriculum-matching design process with teachers, 8 Maker activities and lesson plans were developed, and implemented in Science and Language Arts classrooms of a school with a large percentage of students from underrepresented populations, over the course of 18 weeks during one semester. Coded videos revealed three categories of Maker activities: those that enabled learning, demonstrated learning, and provided learning of the concept itself. Experiences of teachers and students also revealed eagerness to participate, engagement, and exploration in the activities, as observed in a series of analyses. Other themes include the importance of multi-sensory exploration and ownership of self-constructed apparatuses with electronics. The resulting Maker activities and lesson plans offer strategies for familiarizing students with electronic tools and fostering tinkering while remaining true to the learning standards of the classroom.

Author Keywords
Making; maker; maker kits; education; curriculum; children; elementary school

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION
This paper investigates how Making-oriented activities may be integrated into the modern classroom. While the potential contributions of Making activities as hands-on learning has spurred interest in its broader use in education [1], the design of curriculum-appropriate Making activities and kits is critical to success in classroom use to support the goals of universal education to which the modern public school classroom is purposed. There are, however, significant challenges that hinder the use of Making-based learning in the classroom, as aptly summarized in Halverson and Sheridan [2]. First, the American classroom is 'learning goals' driven, while Making is exploratory, creativity- and innovation-driven [3], so educators often do not see the value/advantage given the pressures they face to meet learning goals and tests. Second, there are few Making activities and kits that have been proven to match learning objectives. The skills and knowledge needed for Making are often not easily matched to curricula. Third, classrooms tend to prize discipline and classroom management [4] and thus focus on order ('a quiet student is a good student'), while in Making, from our experiences, some degree of 'rowdiness' is unavoidable. These challenges result in most Making-oriented activities and kits being designed for and tested mostly in workshops and after school programs rather than in a classroom with a broader base of learners.

Our work addresses the challenge of integrating Making into the elementary school classroom using the prediction that a compromise can be made between managing order and learning in the classroom and providing opportunities for tinkering and exploration, and this will result in successful engagement in Making without the sacrifice of school curriculum. Here we test this, reporting on our Maker kit and activity design and use in third- to fifth-grade classrooms. The school where our studies were conducted serves a diverse population with Latino students (≈72%), African Americans (≈25%), and other (≈2%). The students come predominantly from low socioeconomic status (SES) households. Underrepresented populations have been shown to benefit from opportunities to work directly in a "high-tech rapid prototyping environment", and that such hands-on activity also promotes motivation to pursue Science, Engineering, and Technology based careers [5]. Giv-

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en findings that workshops with underrepresented students can promote interest in STEM and assist in the development of skills necessary for STEM careers, our study aimed to provide an understanding of what is required for a successful Making intervention in the classroom that both engages students and satisfies curriculum goals. Findings from our study contribute greatly to the field in that our Maker activities were designed through an intense collaborative process with the teachers, are curriculum-based in nature, and were conducted in a school with populations typically highly underrepresented in STEM careers.

In the rest of the paper, we first lay out our perspective and theoretical foundation on our approach to integrating Making into the classroom for children. We then describe our semester-long study and present the findings and insights based on our experiences, video analysis, and student questionnaires analysis.

MAKING AS THE NEW COLORED PENCIL

Following Dewey's *learning by doing* [6] adage where students learn through the practice of a concept, and Piaget's constructivist theory of children as active learners who build on prior knowledge schema [7], hands-on learning through designed classroom laboratory exercises have been integral parts of science education. Making moves beyond hands-on learning, requiring tinkering and experimenting to produce "artifacts that are technologically-enhanced" [8]. Making, with its 'Do-It-Yourself' construction of artifacts through 3D printing, electronics prototyping, and crafting is well-positioned to foster engagement in the classroom, as well as promote a deeper interest in STEM among underrepresented students.

As Resnick and Rosenbaum have argued, the benefits of Making that extend beyond the activity into the adaptive skillset include the *tinkering* approach to thinking and problem solving [9]. Tinkering can provide an approach to learning that puts the focus on discovery, new experiences, and experimentation. This "bottom-up" approach can provide opportunity for learning something new that a top-down approach may have prevented in its pre-determined, often biased, and narrowly-focused method. Furthermore, a student who is continuously taught to approach learning and problem solving with the goal of arriving at a correct answer may become discouraged when he or she is unsuccessful. However, a student who sees opportunity for exploration, without the risk of failure or embarrassment, may be encouraged to continue learning about a concept.

We encapsulate our approach to children's Making in the formal context of the classroom in the term 'Making as the new colored pencil'. Not every curriculum topic is obviously translatable into a practical classroom session involving 'Making' per se (i.e., the topics of 'electricity' and 'parallel and series circuits' are easily taught using Making activities, but it may be less immediately clear on how to use Making to teach the topics of 'natural resources' and 'oil formation', or vocabulary learning, etc.). In our study, we employ the requirement that curriculum-integrated Making activities are those that enable children to construct their own apparatus to learn. In this model, each activity is purposed so children could actively create the tools needed to initiate their own learning events; similar to chemists from previous generations who blew glass for their own pipettes, or psychologists who built mazes and experimental apparatuses. Children learning to use glue or colored pencils are not taught the composition of glue or what graphite is, or what pigments are used in paint and crayons. In Making then, children can be introduced to the 'art of Making' before they are fully versed in basic electricity. This knowledge can be expanded upon incrementally over time, possibly inspiring new ideas and innovative solutions.

RELATED WORK

Little prior work has proposed broad-based approaches to inform the design of Maker kits with a view towards full integration into a formal learning context such as instruction in the school system. Empirical research with a focus on learning through Making includes, for instance, Posch and Fitzpatrick [10] who report case study experiences of children aged 10 to 14 years old attending a workshop at a FabLab that provided instruction on 2D and 3D design and fabrication, printed circuit board (PCB) fabrication and assembly, and software programming. Flores and Springer [11] describe the assessment of self-directed learning that occurs in the Makerspace created at the Hillbrook Middle School to support science curriculum. They draw out several guidelines from their experiences: the need to allow for iteration in assessment and the need to allow for experimentation time as opposed to strictly structured classes, allowing students to set their own goals for the day.

In the Robot Diaries project [12, 13], middle school students are made to design "affective, programmable tangible communication devices using familiar crafting materials and then use motors, lights and computation in novel ways to animate their creations". The project was tested in a six-session workshop with 7 participants. Video-based analysis was done, and brief reports are presented on whether the children learned, and what they learned. They found increases in learning specifically for robotic components. Qiu and colleagues [14] organized 3 individual workshops on computational textiles where middle and high school students used the LilyPad Arduino toolkit with a designed STEM curriculum to create different artifacts. Survey questions were administered to measure the children's attitudes toward programming and electronics before and after the workshop. The Fab@School study by Alexander and colleagues [15] studied the implementation of activities that integrated digital fabrication into math and science 4^{th}- and 5^{th}-grade classes with the help of pre-service teachers across two schools. The intervention activities in the classroom included, for example, creating virtual 3D models, constructing those models into physical objects with cardstock and other materials, and re-designing the models based on initial testing. Through the use of a validated Math and Science instrument, the study reported positive gains in students' perceptions towards STEM.

OPERATIONALIZING THE COLORED PENCIL APPROACH

In our project, we operationalized our approach of curriculum-integrated Making as the 'new colored pencil' as described below. The foundation for our Making activities involved the basic electric circuit shown in Figure 1. The circuit generally comprised a battery, a crafted switch

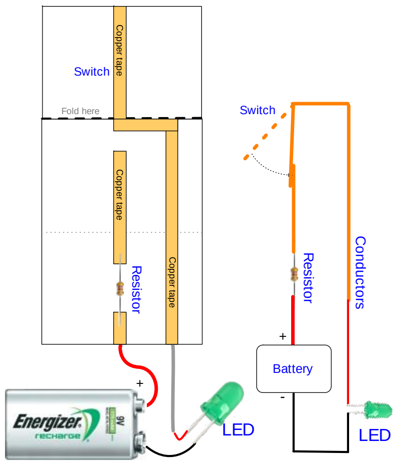

Figure 1 Switch-card sub-assembly

with an embedded resistor, and a load (a light-emitting diode or LED in the figure). For different projects, the load may be replaced with a geared rotational motor, a vibrating motor, an incandescent light bulb, or multiple loads in series or in parallel (as in the case when the curriculum segment specifically addressed series and parallel circuits in the 5th grade). In most projects, the switch cards and batteries were mounted on a 'circuit board' that is printed on standard 8½" × 11" card stock to guide the students on layout and connections. In the course of the school term of our extended study, each student saw and wired this general circuit configuration in 8 separate projects with different loads, batteries (9V and dual AA batteries), and the presence of switches (in some projects a motor or incandescent light bulb may be connected directly to a battery). The intention is that the children will generalize their learning of the basic circuit through exposure to different configurations.

In various projects, the Making materials may include 3D printed parts. We describe examples of these 3D printed parts later in the paper in the form of plastic 'mixer heads' that are attached to rotating motors for the '*Mixtures and Solutions*', and a 'drill' or 'augur' head used in the '*Natural Resources*' curricula pieces (see section on 'Description of Maker activities' later in the paper). The students are not just handed the parts. They are told that the parts were 3D printed. The intention is that the children will be introduced to 3D printing in a later school term, and they will expand their 'tool repertoire' as they progress in their elementary education. In this way, throughout the different activities, the idea that the students are making the apparatus to support their own learning is reiterated.

Learning about the apparatus is obviously not the sole purpose of our curriculum integration. The students learned different science and language-arts topics. For example, in the '*Rapid changes in the earth*' curriculum segment, the children use vibrating motors to shake a tectonic plate model that causes the collapse of model houses (see Figure 2) to understand that earthquakes occur through powerful shaking of the underlying plates. In some curriculum segments, the students do learn about topics directly related to the electrical circuits (e.g., when the 5th grade students learned about series and parallel circuits, or when the topic is about energy conversions of electrical to mechanical energy).

STUDY DESCRIPTION

Our study followed third, fourth, and fifth grade classrooms of a local elementary school. Two classes for each grade were selected in collaboration with the school's administration. We designed and implemented eight different Maker activities through a curriculum-matching process for each of the six classes. For each class, we met with the teacher for a semi-structured interview prior to the designated week that we would be implementing the Maker activities in the classroom in order for the teachers to participate as design informants. This study was conducted in an 18-week semester. For each of the six classes, Maker activities were implemented for each school day during a total of three weeks.

During each class, we placed cameras and audio recorders at each table to capture the speech and activity of each group of four to six students. The class sizes ranged from 18 to 25 students. This resulted in 124 students participating in the program in total. Each teacher interview was recorded as well. During Maker activities, researchers were present to assist students and teachers and answer student's questions about the Maker activities. The teacher instructed the students and guided them through the Maker activities for each day. All students provided verbal assent to participate, and parents signed consent forms prior to video and audio data collection. All procedures were approved by our Institutional Review Board.

Our Design Process

Our design process evolved throughout the semester of our study. Generally, it consisted of a series of stages that began with an initial collaborative planning session with the teachers. During this session we were informed of the state-designated curricula plan for Science and Language Arts classes for the semester. Our design team then initiated a group brainstorming session one month before implementation in the school. During this brainstorming session, the curricula topics and associated learning goals were used to develop Maker activities that would serve as opportunities for the learning goals to be understood through the vehicle of Making. Three weeks before implementation in the school, the lead designer developed technical sketches of each Maker activity into a prototype for testing to ensure that each Maker activity met the learning goals and the electronics could be easily manipulated and used to complete the activity. Following these initial tests, the lead designer began manufacturing materials for each student in the class.

Two weeks before implementation in the school, the lead designer met with the teachers to present the prototype, receive feedback and possible suggestions for lesson plans to incorporate the Maker activity, along with minor modifications to the proposed prototype. For example, one design involved the making of Red-Solo cup robots to represent characters in a language arts class. The designers built a prototype of the robot and showed it to the teachers for feedback. This is important because, without seeing the robot, the teachers would have difficulty envisioning their lesson plan. The proposed Maker activity outlined to the teachers how the children would participate using the electronics to create the artifacts to engage and enable learning of the curricula topic. This method was used to inspire teachers to draw from their skillset examples, demonstrations, and explanations that they could use to introduce the Maker activity, as elaboration during the Maker activity, or as a conclusion to the Maker activity.

Finally, one week before implementation of the Maker activities in the classroom, our team met once again with the teachers to run through the Maker activity to ensure teacher understanding and ability to instruct the Maker activity. The goal of this design process was for the teachers to be active instructors of the Maker activity and to realize and discover new ways of thinking about their lesson goals and curricula using the landscape of Making to uncover hidden opportunities to promote student learning and engagement in the classroom.

DATA ANALYSIS

Our semester-long study working with the teachers and in the classrooms resulted in 3 types of data that we focus on in this paper: A) A series of curriculum-integrated Making activities that resulted from our process; B) Feedback on the activities from self-report usability questionnaires from the children; and C) Teachers' interview transcripts and videos of the children engaging in the Making activities in the classroom.

The Making activities themselves were then analyzed at a higher, abstracted level to find commonalities and differences and ability to increase engagement in the classroom. The goal of this content analysis exercise was for us to gain an understanding of the types of activities that we generated using our design process throughout the semester because we did not have pre-determined categories of Maker activities. The usability scores from the children's questionnaires were obtained for each Maker activity in order to determine the activity's ease of use and self-reported understanding of the electronics and procedures used to create tools for classroom learning, as well as the level of enjoyment resulting from the classroom intervention. Given that disruption in learning can occur when students are unmotivated, disengaged, distracted, or frustrated [16], these scores were necessary to test whether the designed Maker activities could meet the classroom management end of our compromise between order and tinkering and experimentation. Finally, classroom videos of 5 Maker activities (one or two representative of each category of Maker activity type that we uncovered) were selected, as well as the corresponding teacher interview videos for those activities. An open coding process was performed on the videos and transcripts of the videos, whereby two independent coders watched all the videos two times. The first pass was to delineate broad themes. The team met, and agreed upon the lists of themes generated, and those themes were synthesized and consolidated. The second pass was to re-analyze the videos to find finer-grain understanding of the initial broad themes uncovered.

STUDY RESULTS AND FINDINGS

A. Curriculum-integrated Making activities

Description of Maker activities

The following details the classroom projects that we produced from our design process with the teachers for each grade, along with the state identified learning goals [17] and the Making activities involved with each project.

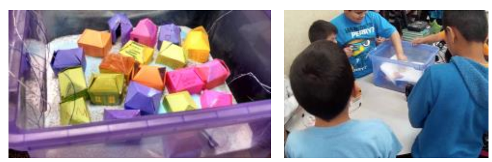

Figure 2 Third grade class working with an earthquake model: L. Model village prior to an Earthquake simulation; R. Making the earthquake simulation

Third Grade Science

<u>*Earth and Space: Rapid Changes*</u>

Learning Goals: Earth consists of natural resources, its surface is constantly changing, and some changes occur rapidly. Examples of rapid changes investigated include volcanic eruptions, earthquakes, and landslides.

Maker activity 1: The students built a model of a village that sits on a pair of foam-core 'tectonic plates' with vibrating motors attached to its foundations (the plates are placed together in a large plastic box on dowel rod 'pillars' that are attached to the plates with 3D-printed mountings). A layer of kitty litter is laid on top of the foam core plates and the students created a village made of decorated origami houses on top of the kitty litter (Figure 2.L.). When the vibrating motors taped to the 'foundation pillars motors are activated, the foam core plates shake and separate, destroying the village and causing some of the kitty litter to fall into the crack of the separated plates. Figure 2.R. shows the students constructing the tectonic plate model.

<u>*Matter and Energy: Changes in Heat*</u>

Learning Goals: Matter has predictable, observable, and measurable physical properties. These properties or states classify matter as solid, liquid, or gas. Matter can change states with heating and cooling.

Maker activity 1: Students melted ice in a cup using an incandescent light bulb attached to a battery to simulate the sun. The students saw that the ice in a cup with a lighted bulb melted much faster than one with no light bulb to provide heat.

Maker activity 2: Students used an incandescent light bulb and electric circuit to demonstrate condensation. A wad of wet paper towels are placed in a plastic container and a lightbulb is suspended into the container on a 3D-printed bulb holder. The container is covered with a paper towel held in place by a rubber band. When the light bulb is left on for a while, water vapor forms in the cup. As the water vapor cooled on the inner surface of the container, water droplets form and are visible on the surface. The students see how heat and cold cause liquid water to become vapor through evaporation and to become liquid water again through condensation (Figure).

<u>*Matter and Energy: Mixtures and Solutions*</u>

Learning Goals: Physical states of matter can be tested, observed, and recorded. Physical properties of matter include temperature, mass, magnetism, and the ability to sink or float. A mixture is created when two materials are combined such as gravel and sand and metal and plastic paper clips.

- Maker activity: Students built an electronic mixer to create a mixture and a solution. The mixer comprised the basic circuit with a geared rotating motor as the load.

Figure 3 Third grade students observing whether condensation occurs in absence or presence of heat

A 3D-printed mixer head is attached to the motor through a dowel rod so that the student can insert the head into a mixing container and activate the motor. The students built a second electric sifting tool to separate the individual parts of a mixture. This comprised simple hand-held sieve with a vibrating motor attached to it. Activating the vibrating motor by depressing the card switch would shake the sieve to separate its contents.

Third Grade Language Arts

<u>*Reading/Comprehension of Literary Text/Fiction*</u>

Learning Goals: Inferences and conclusions can be made about the structure and elements of fiction using evidence from text. Students can:

(a) sequence and summarize the plot's main events , while explaining how they can influence future events;

(b) detail character interaction using changes and relationships

(c) recognize first or third-person narrators

- Maker activity: Students decorated a Red-Solo cup robot (Figure 4) from using colored paper cut into different shapes to create a robot character that fit certain context clues. Three popsicle sticks taped to the inverted cup served as the legs of the robot, and a vibrating motor was attached to one of the legs. When the motor is activated using the card switch, the legs vibrate causing the robot to move around.

Figure 4 Third grade students making Red-Solo cup robots in a language-arts class: L. Reading fictional stories to find context clues, which they used to create a robot; R. Making their robot character move by assembling circuits with a connected electronic motor

<u>*Reading/Vocabulary Development*</u>

Learning Goals: Students can:

(a) understand and use common prefixes (e.g., in-, dis-) and suffixes (e.g., -full, -less), and know how they change the meaning of roots;

(b) use context to determine meaning of unfamiliar words or select among multiple meaning words and homographs;

(c) understand and use antonyms, synonyms, homographs, and homophones;

Maker activity: Students made projection boards (Figure 3. L.) using LEDs and electric circuits. The board features four LEDs mounted on dowel rod rails attached at the back of a foam-core board with rectangular windows cut in it to correspond with the path of the LEDs on the rails. The rails are held in place by 3D-printed end pieces glued on the board, and the LED is mounted on another 3D-printed slider. A transparency sheet is placed between the LEDs and the foam-core board. The students or teachers wrote sentences on the transparencies in spaces that align with the cut-out windows. A vellum sheet is glued to the front of the foam-core board to serve as the projection screen. As a LED slides along its rail, words on the transparency are projected onto the vellum screen as they are highlighted by the LED. The students use the board to move light to focus on the words of a sentence to learn the meanings of unfamiliar words in context.

<u>*Reading/Comprehension of Informational/Expository Text*</u>

- Learning Goals: Students can:

(a) identify which details or facts support the main idea;

(b) support conclusions and arguments with textual evidence;

(c) identify cause and effect relationships; and

- Maker activity: Students made Quiz boards that comprise four LEDs with independent switches attached to a foam core board. A question is taped to the top of the board, and answer choices are taped next to each of the four LEDs. The students could select from among the choices by activating the card switch that lights the appropriate LED. They students played in teams against their peers, while answering questions about passages from the class (Figure 3.R.).

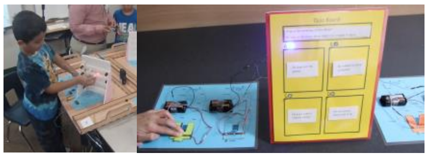

Figure 3 Third grade projection and quiz boards: L. Student using the projection board to learn new vocabulary; R. Quiz board

Figure 4 Fourth grade class model prior to earthquake simulation

Figure 5 Fourth grade water cycle activities: L. Students simulating condensation in the water cycle, R. Students building a lighted diorama of a water cycle

Fourth Grade Science

<u>*Earth and Space: Rapid Changes*</u>

Learning Goals: Natural resources are found in the earth, and rapid changes occur in the Earth's surface such as volcanic eruptions, earthquakes, and landslides.

Maker activity: The fourth grade students made the same earthquake model as described for the third grade. Figure 4 shows how the fourth graders laid out their switch boards with respect to the earthquake model. The difference between the fourth graders' exercise and that of the third graders is that they discussed the model with greater sophistication.

<u>*Matter and Energy: Water Cycle*</u>

Learning Goals: The student is expected to predict the measurable changes to matter caused by heating and cooling, such as ice becoming liquid water and condensation forming on the outside of a glass of ice water.

Maker activity 1: Figure 5 shows fourth graders using the same incandescent light bulb ice melting apparatus as was discussed for the third graders earlier. The difference was in the depth of understanding about the science of the water cycle.

Maker activity 2: Again, the fourth grades built the same apparatus as the third graders for evaporation and condensation to support their learning of the fourth grade science.

- Maker activity 3: Students designed and created lighted dioramas of the water cycle using foam board, LEDs, and electric circuits (see Figure 7). We defer the description of dioramas to our discussion of fifth grade science activities.

<u>*Matter and Energy: Mixtures and Solutions*</u>

Learning Goals: The student can measure, test, and record physical properties of matter, including temperature, mass, magnetism, and the ability to sink or float; compare and contrast a variety of mixtures and solutions such as rocks in sand, sand in water, or sugar and water.

Maker activity: The fourth grade students made the same mixer as did the third grade students to study mixtures and solutions at the fourth grade level of understanding.

Fourth Grade Language Arts

<u>*Reading/Vocabulary Development*</u>

Learning Goals: Students understand new vocabulary and use it when reading and writing. Students will:

(a) understand the meaning of common prefixes (e.g., in-, dis-) and suffixes (e.g., -full, -less), and know how they change the meaning of roots;

(b) use context to find the meaning of unfamiliar words or choose among multiple meaning words and homographs;

(c) understand antonyms, synonyms, homographs, and homophones;

- Maker activity: The fourth grade students constructed and decorated the same Red-Solo cup robots as discussed earlier for third grade. The fourth graders used the exercise to create characters to demonstrate language mastery of the fourth grade level text in their class assignment.

<u>*Reading/Comprehension of Informational/Expository Text*</u>

- Learning Goals: Students can:

(a) understand details or facts that support the main idea;

(b) support conclusions and arguments with textual evidence;

(c) understand cause and effect relationships among ideas in texts; and

- Maker activity: The fourth graders used the same LED quiz boards as the third graders to support their reading and comprehension goals of this learning unit.

Fifth Grade Science

<u>*Earth and Space: Earth Changes and Fossil Fuel Formation*</u>

Learning Goals: Earth contains useful resources and its surface is constantly changing. The student understands the processes that led to the formation of sedimentary rocks and fossil fuels.

Maker activity 1: The fifth grade students created a model of sedimentary layers using layers of kitty litter, spinach, and salt inside a transparent cylindrical plastic container. This allowed the students to observe the different layers that simulate the layers of sedimentary rock as they would form naturally over time (Figure 8). To create each layer, the students would spread a mixture of the salt and kitty litter on top of a layer of spinach leaves using the same motorized sifter that was used in the Maker activity on Mixtures and Solutions. The students observed the spinach as it became rancid over the week.

Figure 8 Fifth graders making light-up dioramas of natural resource formation (top left and bottom). Fifth graders make electronic drill to uncover layer of spinach in model of oil formation

Figure 9 Fifth grade student diagraming parallel and series circuits

Figure 10 Fifth grade students measuring refraction angle from the LED they connected

Maker activity 2: Later in the week, the students built an electric motorized drill to uncover the "fossilized" spinach to simulate how fossil fuels would be extracted from beneath the earth. They attached a 3D-printed augur head at the end of a dowel rod onto a geared rotating motor. This allowed them to dig through the layers of salt and kitty litter to get at the decaying spinach.

Maker activity 3: The students built a lighted diorama of the formation of fossil fuels (Figure 8). They designed posters that illustrate their understanding of earth sediments and fossil fuel formation using colored markers. These posters were taped onto foam core boards and the students adorned the board with LEDs by poking the LEDs through the foam core board and connecting up the circuits. These LEDs are located on the posters by the students to highlight key points in the illustration. The dioramas were used by the students to present their understanding of the science to the class.

<u>*Force, Motion, and Energy: Electrical Energy*</u>

Learning Goals: The student can demonstrate that the flow of electricity in circuits requires a complete path through which an electric current can pass to produce light, heat, and sound.

Maker activity: Students created parallel and series circuits using incandescent light bulbs and batteries. They observed how the bulbs decreased in intensity if they were connected in series, and how removal of a bulb in a series circuit would cause all the lights to go off. They also observed that the same did not occur if the bulbs are connected in parallel. The students traced the circuits to understand if the circuits formed closed loops. They detailed their understanding of the different circuits in their journals (Figure 9).

<u>*Force, Motion, and Energy: Properties of Light*</u>

Learning Goals: The student can show that light travels in a straight line until it strikes an object or travels through one medium to another and that light can be reflected using mirrors or other shiny surfaces and refracted when observed through water.

- Maker activity 1: Students constructed a circuit to light an LED. The LED was placed on a sheet of paper with printed target and mirror positions, and they observed how surfaces of different specularity and color reflected light differently.
- Maker activity 2. The students constructed the same LED circuit and observed it through a plastic container of water (Figure 10). They looked through the water at the LED and aligned their line of sight with a ruler. When they drew a straight line in the direction of the ruler, they observed that the line would miss the LED. When they aimed the ruler at the LED without the container of water, the line projection from the ruler would hit the LED. From this they understood that the light from the LED bent or refracted as it passed through the water.

<u>*Matter and Energy: Mixtures and Solutions*</u>

- Learning Goals: The student can show that some mixtures maintain physical properties of their ingredients, such as iron filings and sand; while other matter changes within solutions, such as salt in water or lemon juice in water.

Maker activity 1: Students used the mixer they built to form a salt solution and a Kool-Aid solution. They heated and evaporated the water to retrieve the salt from the saltwater solution, and made the Kool-Aid solution more concentrated (Figure 11).

Fifth Grade Language Arts

<u>*Reading/Vocabulary Development*</u>

Learning Goals: Students can create summaries and paraphrase text in ways that maintain meaning and logical order. They can stop reading and make connections in the text (e.g., between characters and themselves/personal experience and the text, other texts, etc.).

Maker activity: The fifth graders decorated the same Red-Solo cup robot used for the third and fourth graders to illustrate their understanding of the fifth-grade-appropriate material they read. They then summarized the stories about the characters represented by the cup robots.

Figure 11 L: Fifth grade students using the mixers they built to dilute Kool-Aid solution. R: The 3D-printed black mixer head, cup, rotating motor, and circuit used during Mixtures and Solutions activities

<u>Reading/Comprehension of Informational/Expository Text</u>

- Learning Goals: Students can:
  (a) create summaries of text in ways that maintain meaning and logical order;
  (b) understand and support the facts in text;
  (c) synthesize and draw conclusions between ideas within a text and across two or three texts representing similar or different genres.

Maker activity: The fifth grade students constructed the same quiz boards used by the third and fourth graders for their fifth grade reading/vocabulary exercises.

Maker activity Categorization

Analysis of the 8 different Maker activities (across grades) revealed three categories. One category of Maker activities ***enabled learning*** and consisted of 40-minute to 90-minute long classroom sessions during which students were instructed to build an electronic apparatus (e.g., a motorized mixer) in pairs to aid with learning the weekly designated elementary science or language arts curriculum topic (e.g., understanding the difference between a mixture and a solution).

In contrast, our analysis of the designed Maker activities revealed that other activities ***demonstrated learning*** rather than enabling learning. These activities consisted of classroom sessions during which the first 10 minutes entailed a teacher-led classroom discussion about the elementary science or language arts curriculum topic (e.g., oil formation), followed by students building an electronic diorama to demonstrate their knowledge of the discussed topic (e.g., a lighted diorama illustrating the layers of sedimentary rock that accumulate over time, increasing pressure and heat).

Finally, a third type of Maker activity resulted in ***learning of the maker tools themselves***, during which students were taught concepts about the electronic tools (e.g., circuits) and were then instructed to build the tools to test learned characteristics (e.g., parallel vs series circuits). One Making activity was chosen from each category to analyze classroom behaviors and activity, as well as teacher feedback and reflection. Therefore, video analyses focused on the Maker activity in fifth grade for parallel and series circuits as an example of ***learning of the maker tools themselves***, the mixtures and solutions Maker activity in third, fourth, and fifth grade, the oil drilling activity in fifth grade, and the earthquake Maker activity in third and fourth grade as three examples of ***enabling learning***, and the lighted dioramas in fifth grade used to ***demonstrate learning*** of natural resources formation over time.

B. Student Feedback about Making activities

Students' scores for the usability of the Maker activity kits are presented in Table 1 for each of the analysis-discovered activity types. All scores were measured on a scale of 1 to 5, with 5 being the largest value.

Type of Maker Activity	Easy to Learn	Easy to Complete	Easy to Remember	Fun
Enabled Learning[a]	4.7	4.5	4.1	4.9
Demonstrated Learning[b]	4.6	4.6	4.2	4.7
Learning of Tools Themselves[b]	4.6	4.6	4.4	4.9

Table 1. Average usability scores reported by students for each type of Maker activity, [a]third, fourth, and fifth grade students, [b]fifth grade students only.

On average, students reported high levels of usability, understanding, and enjoyment of each type of Maker activity. Because the design of the Maker kits included a printed "circuit board" to help guide the students in electronic circuit construction, students were allowed to explore and experiment with the electronic components while in the boundaries of the classroom's time constraints and scheduled lesson plan. In this way, we could fulfill the requirement of classroom management in our Maker intervention.

C. Video Analysis and Teachers' Interviews

Below we provide a descriptive account of the five themes discovered during the first round of video analysis. These finer-grain descriptions of events were coded during the second round of video analysis.

Multi-Sensory Exploration

Even with the use of "circuit board" guidelines, each type of Maker activity demonstrated tinkering and exploratory behavior. We observed these behaviors most often when each student in the pair had an active role to perform, rather than the role of passive watching while his or her partner built. After passive watching, students were more likely to become distracted or disengaged from the activity. Instances when students were able to familiarize themselves with the electronics were made possible via multi-sensory exploration, when the artifacts they made were more closely associated with continued engagement in the Making and the Science or Language Arts lesson. In other words, students took advantage of the entire time they were given to practice building their circuits and making the tools. On many occasions, students were observed trying to figure out the components on their trays, or just exploring further with what they had. For example, during the circuits experiment with fifth grade, one of the students was trying to connect and disconnect the circuit repetitively and observed the LED turning on and off with each iteration. Similarly, teachers viewed activities in which each student engaged actively with the making as a successful learning event. During the design phase, when the Maker activity for earthquakes was proposed as a classroom-wide single model, both fourth grade teachers requested modifications so that each student had a clear and continuous Making task.

Engagement with regards to the students can be understood as fixed attention and active interest (commenting and asking questions). The projects were characterized as having attributes that can be touched, held, seen, heard or even smelled. Teachers noted that it allowed students to comprehend what were inherently abstract concepts. In addition to clarifying conceptual material, it also enabled prolonged attention on the part of the students when in use. Students had a space where they were able to explore, intended or not. Because the Maker activities were co-designed with teachers and structured to target key lesson plan demonstrations (e.g., building the mixer and then using it to make a solution and a mixture), students were not given a designated time to explore the possibilities of 'Making' resources. Despite this, students were found in all three types of Maker activities to engage in self-exploration (e.g., making the mixer head "dance" across the table or comb their hair).

Exploration occurred in instances whenever students were either setting up initially, ahead of their given task at any point in time, or even when they were off task. For example, in the 'oil formation' Maker kit, one child initially assembled the drill and observed how it worked outside of the litter and within. The child would repeatedly move it in and out to observe its effects. Afterwards, the child removed the electrical components of the drill, and manually rotated it to have a more controlled examination of how the spinach was being extracted from the kitty litter. Exploration here enabled further understanding by investigating the nature of the tool and the concept that it represents.

Ownership and Accomplishment

In a number of instances, the children were observed showing confidence and pride in what they had learned or had made. These included showing the mixer that they had made to researchers or teachers. Also, the fifth grade teacher reported a case occurring after the mixtures and solutions Making session, in which one student felt such confidence in his knowledge that he came to her and requested a test. The teacher also said that because he was not the kind of student who would normally enjoy test-taking, she felt that this showed that the Making activity had an impact on the student's confidence and self-efficacy.

Some students were given the opportunity to demonstrate their mastery of the subject by means of a presentation. In these instances, students were tasked with making use of existing Making knowledge to best design a visual representation of their knowledge. Students were able to design their presentations as they saw fit within the subject matter and found various ways of representing the information through the position of LEDs in their dioramas and the sequence of lighting the LEDs during the presentation. This allowed students to express themselves, potentially leading them to take ownership of their knowledge. This encouraged students to want to demonstrate their project to the class, as seen in the children's own eagerness in presenting their work, as well as their line of questioning of how something was represented. Afterwards, the fifth grade teacher expressed how pleased she was with the Making activity and compared the event to visiting a museum and seeing the displays light up in various sequences. Observations of ownership and accomplishment may be the key to promoting underrepresented students' interest in STEM. Making activities integrated into the classroom can create opportunities for increased confidence and pride in using electronics and creating electronic tools. Taken together with the usability scores reported by this population, our results demonstrate a potential classroom intervention to promote STEM interest and Making familiarity for a type of student previously shown to benefit from Making [5].

Teachers' Contributions

Teachers viewed the Maker activities as ones that needed to be supplemented with additional real-world examples and visual demonstration. But they also capitalized on the insight and inspiration sparked by the Maker activities to elaborate on the curriculum topics and concepts. For example, a fifth grade teacher offered a dilution experiment to demonstrate an additional use of the electronic mixer, and a fourth grade teacher realized that the cup robots could be used to enable children to understand context clues by having to create a character that matches a story description with unfamiliar words. Furthermore, our design team drew upon their own previous designs to help solve current design problems. Maker activities influenced our own design, as well as the teachers' ideas and instruction, and students' learning. The integration of the Maker activities in the classroom setting helped to enhance and enrich the landscape from which visual demonstration and real-world examples are chosen, while also promoting interest in and experience with technology.

Sources of Knowledge Needed

Analysis of the coded teacher interviews revealed that the lead designer needed to rely on more than just knowledge of design and manufacturing to create the Maker activities to present to the teachers during the initial prototype presentation. The entire design process was altogether more efficient and more successful, resulting in a well-understood and easy-to-use product, as reported by teachers and as observed in classroom videos, if the lead designer used three other sources of knowledge, in addition to keeping the manufacturing process in mind: i) knowledge of the Science or Language Arts concept should be explained; ii) how the Making activity should best be carried out in the classroom to ensure that every child could understand the purpose and how the activity was intended to occur; and iii) how to explain the Maker activity in a way that stimulated enthusiasm, without encouraging distraction or disruptive behaviors. In fact, one fifth grade teacher explained that a successful Maker activity would involve the design team and the teachers "meeting in the middle," such that both parties would offer their own expertise, while considering the other party's perspective in the design and planning phases.

Challenges with Classroom Making activities

Across all three types of Making activities, it was noticed that there was a debilitating dynamic that existed between certain pairs of students. It was often observed that one child held a dominating role while the other assumed a passive role. This manifested when the dominating child took the resources necessary for Making and continued ahead with the activity, reducing the passive child's involvement. At times the passive child either stood back and became an observer or, in others, become withdrawn from further activity.

In one case, it was observed that the roles can be exchanged within the same period where the passive child asserts herself, taking over and causing the dominant child to withdraw from further activity. This peer-to-peer domination dynamic is problematic for various reasons across the levels of observation of the class. Collectively and potentially individually, the knowledge that results from participating in Making is reduced resulting in incomplete knowledge for the student. At a class-wide level, this potentially means additional time taken away from helping other students to address known educational related issues in managing these students, should they come to be disruptive between one another and those around them.

DISCUSSION AND CONCLUSION

Many researchers stress that Making is an approach to thinking and solving problems that goes beyond the context of the classroom and extends to a social group of like-minded individuals who value discovery and exploration [3, 18, 19]. Our study illustrates a potential strategy for introducing the social dynamic of shared interests in Making into a formal classroom setting that is designed to support universal education. For instance, the designer needs to ensure that each child has an active role within the Maker activity itself. In other words, as was the case with the 'Dominant Child Syndrome' that we described before, when designing activities for classrooms that rely on peer to peer relationships, there is a need for a design for "cooperation" in mind. What this means is that activities ought to be designed in a way to make it difficult for an individual actor to complete on their own, necessitating a need for a partner to assist in the proceedings. A more specific way to address this is to designate specific roles within the activity to students to encourage cooperation.

We conducted a semester-long study where we worked with elementary school teachers as informants to design Maker activities that would fit into the Science and Language Arts curricula of the third, fourth and fifth grade. We began with the approach of viewing curriculum-integrated Making as the 'new colored pencil' of modern education. We operationalized this perspective into a design approach, which resulted into a series of Maker activities for third, fourth and five graders from a school that has a large percentage of children from underrepresented populations. These students' usability scores and classroom behavior demonstrated engagement, tinkering, and exploration without the need to sacrifice curriculum and structured lesson plans. .

This study details the outcomes observed following the design and use of Maker activities in the classrooms of a school serving children from underrepresented populations with the hope to later help integrate the students more easily into broader society and STEM careers. However, the resulting themes of two-step open coding analyses of classroom and teacher interview videos can guide the design of future Maker kits that aim to be used in both formal and informal learning contexts for children from the general population. The inclusion of structure, time constraints, and guiding "circuit charts" did not prevent exploratory and tinkering behavior in the students. Students took advantage of the time they were given to discover alternative uses of the constructed tools. When the Maker activity was used to teach the tools themselves, as in the activity about parallel and series circuits, students used repetitive behavior to observe causality. In this way, the students were able to build the tools to initiate their own learning events. Maker activities that match curriculum can be implemented also as an assessment tool to allow mentors or educators to gauge understanding and to allow children to express confidence and pride in the created artifacts that demonstrate learning. Teachers can also benefit from the co-design process of Maker activities that can lead to thinking about curriculum concepts in a new light, such as how to inspire engagement and active participation in technology learning without sacrificing learning standards and classroom order.

SELECTION AND PARTICIPATION OF CHILDREN

The local city's state school where this study was conducted serves a diverse population with Latino students (≈72%), African Americans (≈25%), and other (≈2%). The students come predominantly from low socioeconomic status (SES) households. The class sizes ranged from 18 to 25 students. This resulted in 124 students participating in the program in total. All students provided verbal assent to participate when the Maker activities were initially described during the first session, and parents signed consent forms prior to video and audio data collection. All procedures were approved by our Institutional Review Board.

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