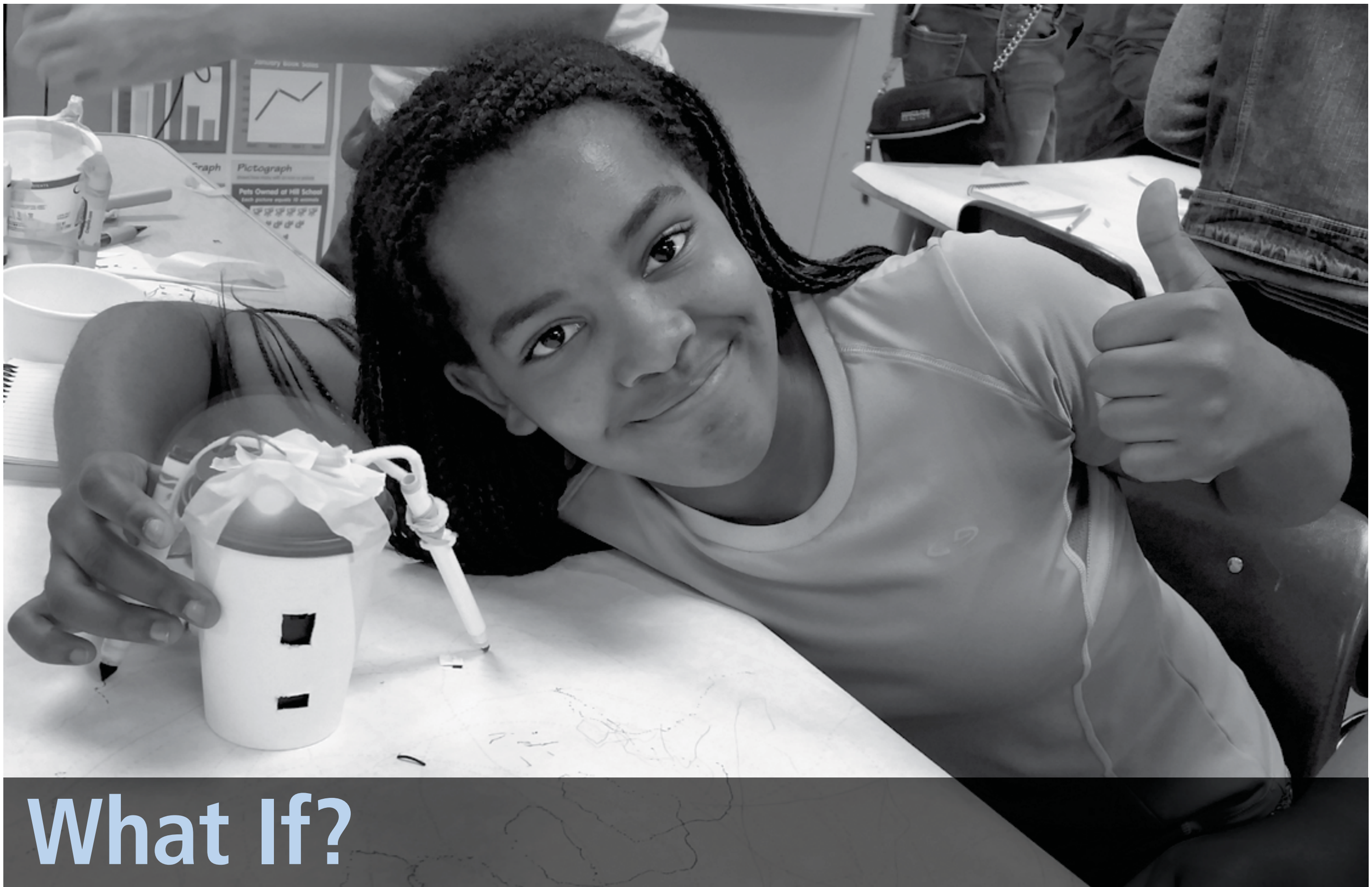

What If?

Building Creative Cultures for STEM Making and Learning

Bronwyn Bevan, Jean Ryoo, and Molly Shea

Active, learner-driven, collaborative activities—a hallmark of youth development—are key to the success of afterschool programming in supporting young people's learning and well-being. How can the field leverage this strength as it seeks to expand STEM programs for young people? (See box "Defining STEM" on the next page.)

This question is especially important for programs serving youth who attend underresourced schools, where opportunities to engage in STEM are less frequent and less likely to be hands-on or inquiry-based (National Research Council, 2012b). Afterschool programs can play a vital role in leveling the playing field by giving young people opportunities, like those common in high-performing schools, to learn STEM by doing STEM (Bevan & Michalchik, 2013). Through *doing* (rather than memorizing) STEM, students can come to understand it as a creative process of inquiry. They can develop positive STEM learning identities that can guide them in future academic and career choices.

Making (see box "Kinds of Making" on page 3) is an approach to STEM education that may be especially well suited to afterschool. Inherently playful, learner-driven, creative, and fun, Making leverages key dimensions of youth development. Research (Peppler, Halverson, & Kafai, 2016; Vossoughi & Bevan, 2014) has found that Making:

- Exercises students' creative and improvisational problem-solving abilities

BRONWYN BEVAN, PhD, is senior research scientist at the University of Washington, principal investigator of the Research+Practice Collaboratory, and co-PI of the Center for the Advancement of Informal STEM Education. She researches how formal and informal learning opportunities can be organized to advance equity in education.

JEAN RYOO, PhD, is an educational researcher at the Exploratorium. She directed the California Tinkering Afterschool Network project. She currently collaborates with Lighthouse Community Charter School in Oakland and with Exploring Computer Science, a K–12-university partnership, to improve STEM and computer science education for all.

MOLLY SHEA holds a PhD in learning sciences from the University of Colorado, Boulder. Her work is focused at the nexus of research and practice in the study of human-centered design interventions to organize for more equitable teaching and learning.

DEFINING STEM

STEM is an acronym whose life began as a set of five words with three commas: "science, technology, engineering, and mathematics." Coined by the National Science Foundation, the term is still often used it in this way.

Over the past decade or more, many have come to think of STEM not as four things but as one: an integrated approach to answering questions or developing ideas that incorporates science, technology, engineering, and mathematics. Some have integrated the arts to produce STEAM. Although school has traditionally separated the disciplines, in the real world, questions are inherently interdisciplinary. Research is often led by teams with different training—in computer sciences, physics, and mathematics, for example—who work together to address a common question.

Making is inherently interdisciplinary. To make something—whether it is a cake or a table-top robot—Makers must use design (engineering), measurement (mathematics), and proportion (mathematics and engineering). Often they are also guided by aesthetic considerations (arts and engineering). STEM-rich Making activities also can involve scientific phenomena, such as electricity or sound, or computer sciences, such as coding. For example, designing and sewing a purse is a Making activity. Designing and sewing a purse using conductive thread and Lilypad mini-processors, a task that can involve wiring, circuitry, and coding, is STEM-rich Making.

This article uses the term "STEM" because the Making activities in our study, which always involved engineering and usually involved science, frequently also involved mathematical practices and sometimes technologies.

- Builds students' agency, persistence, and self-efficacy
- Helps students to deepen and complexify ("level up") their STEM understanding through iterative processes of design, testing, redesign, and refinement

Making doesn't *look* like STEM; it therefore may appeal to young people who aren't automatically drawn to STEM activities. Making has been described as having low floors, high ceilings, and wide walls (Resnick & Silverman, 2005). Because there is no one "right way" to develop a Making activity, learners start with what they know and are interested in; then they advance their thinking by trying out and developing their ideas.

Making's iterative processes—design, build, test, redesign, retest—are fundamental to STEM practices (Quinn & Bell, 2013). Indeed, design failures can be powerful moments for learning, as they are for real scientists and engineers, if students are supported to notice what caused the failure, redesign based on evidence, and retest (Vossoughi, Escudé, Kong, & Hooper, 2013).

"Fail fast, fail often" is the motto of Silicon Valley, the birthplace of the Maker Movement. Making is commonly heralded as an opportunity to "celebrate failure." However, many have noted that assumptions of privilege underlie this celebration of failure (Buechley, 2013; Martinez & Stager, 2013; Vossoughi, Hooper, & Escudé, 2016). It's easy to fail when one can afford to fail. Youth from economically and racially marginalized communities attend schools in which missteps of any kind are likely not to be tolerated. They may not be in a position to celebrate and learn from failure as readily as youth from communities of privilege (Ryoo, Bulalacao, Kekelis, McLeod, & Henriquez, 2015). Educators need to address and model the ways in which failure is a part of the creative process. Young people must experience moments in which things fail as moments in which to learn how things work, not as moments in which they themselves have failed. Explicit attention to this process can build young people's confidence and identity as STEM learners.

This article shares the results of a research-practice partnership involving four afterschool programs serving youth from marginalized communities. Over three years, the project identified key characteristics of inclusive and equity-oriented Maker activities and facilitation. It also defined the kinds of professional development afterschool educators need to support the creative intellectual risk taking that makes Making a powerful context for STEM learning. The results of the study can support the expansion of inclusive Making programs that are equitable for all youth.

Making and STEM Practices

Research shows that to learn STEM, young people must "do STEM," that is, engage in STEM practices. In 2012, the National Research Council (NRC, 2012b) issued a report that detailed eight practices of scientific and engineering inquiry. It found that engaging in these practices provides the best context for learning STEM concepts and skills. Researchers have parsed these practices into three clusters of activity (McNeill, Katsh-Singer, & Pelletier, 2015):

- **Investigating practices**: asking questions; planning and carrying out investigations; using mathematical and computational thinking

KINDS OF MAKING

Three broad types of Making programs are distinguished by their purpose. Some programs focus on entrepreneurship, others on workforce development, and yet others on broadly educative goals (Vossoughi & Bevan, 2014).

Within educative Making, there are again three types:

In *assembly*-style Making, learners follow step-by-step instructions to produce identical or nearly identical objects.

In *creative construction,* learners are given a challenge to address or a model to replicate, but they make choices about the look, scale, and sometimes behavior of the object. The result is many different versions of the same type of object.

In *open-ended inquiry,* learners develop their own ideas and figure out how to make the objects they have envisioned. The result is a wide range of objects, designed to address unique purposes and goals.

This last form of educative making is sometimes called "Tinkering" because of its emphasis on creative, improvisational problem solving. Students may, for instance, develop projects such as a ping-pong table whose net lights up in reaction to a ball coated in conductive paint, a self-zippering jacket that opens and closes based on external temperatures, or shoes for visually impaired wearers that alert them when an object is within 10 feet of their toes. This kind of Making provides a profound example of interest-driven, student-centered learning.

But all kinds of educative Making can give students a concrete purpose for engaging with STEM. Students learn about electricity and batteries not to pass a test but to successfully build a Bluetooth-enabled radio housed in an antique radio shell. Young Makers can not only develop a wide range of STEM skills, such as measurement, scaling, design, and data analysis, but also grapple with STEM concepts such as forces, balance, circuits, and cause and effect—all while engaging deeply in practices of scientific and engineering inquiry.

- **Sensemaking practices**: developing and using models; analyzing and interpreting data; constructing explanations
- **Critiquing practices**: engaging in argument from evidence; obtaining, evaluating, and communicating information

This vision of STEM learning emphasizes the firsthand *phenomena* of science, instead of text-based or abstract *representations* of science. For an example, see the box "STEM Practices in a Making Activity" on the next page. Learning STEM and coming to want to learn STEM, according to current research, requires engaging with real stuff in the real world. Such engagement can motivate interest and a need to know about more abstract concepts.

The NRC vision of STEM learning also emphasizes the role of evidence and the critique of evidence in scientific meaning making (2012b). Unless students have experiences collecting data, testing hypotheses, and considering competing evidence-based explanations, they may miss the most critical dimension of real-world science and engineering: its evidence-based nature.

However, the report finds that few students gain such experience in the classroom, and even fewer in schools that are underresourced (NRC, 2012b). Afterschool can thus play an important role in leveling the playing field by giving students opportunities to engage in STEM practices.

Making provides direct, immediate, and concrete evidence of students' understanding. If students' understanding about how to wire a battery and motor is incorrect, their NatureBots will not locomote. In response, they need to closely examine their design choices, recognize where their understanding or technical skills went awry, and adjust accordingly. In addition, Making can be implemented in ways that require students to systematically collect and record data. Makers can be asked to explain their thinking in journals or during share-outs in circle time.

Investigating STEM-Rich Making in a Research-Practice Partnership

This article outlines key findings of a study of STEM-rich afterschool Making programs offered by the four organizations participating in a project called the California Tinkering Afterschool Network. Two of the organizations, the Fresno Community Science Workshop and the Watsonville Environmental Science Workshop, organized their entire programs around Making. These programs took place in designated workshops replete with a wide variety of materials, tools, and models of past Maker projects. These sites operated as community drop-in centers, welcoming family members of all ages. In both places, many of the paid staff had themselves been drop-in participants when they were

STEM PRACTICES IN A MAKING ACTIVITY: PAPER CIRCUITS

Paper Circuits is a Making activity that extends students' understanding of how to construct an electrical circuit. Students use a variety of paper, paints, and other art supplies to create a greeting card. With copper tape and a battery, they integrate LED lights, so that when the card is opened, a circuit is closed and the LEDs light up.

This activity uses all three kinds of STEM practices identified by McNeill and colleagues (2015).

Investigative practices. Students first develop an idea about the kind of card they would like to create. Then they plan and sketch out their designs, building on the conceptual models they have developed about how circuits work. The open-and-close mechanism of the paper card requires them to extend their circuitry models to function across different planes. They need to figure out how opening a card can complete a circuit without letting copper tapes touch so they short the circuit.

Sensemaking practices. Students' initial designs frequently do not work. They need to rethink their models of circuits and troubleshoot to solve the problem. The card itself provides immediate feedback, or evidence, about the accuracy of their conceptual models and design solutions. If it lights up intermittently, weakly, or not at all, students have to determine if they need to add a second battery, devise a new switch, or rethink their design. The aesthetic and personal components of their creative vision serve as constraints to the design and engineering processes.

Critiquing practices. In Making, the object itself—whether and how it works—provides a powerful critique of the students' thinking and conceptual models. Additionally, students can share their processes of designing and building, even in cases where they cannot get the circuit to work. They can articulate why or how it works—or doesn't—and share with one another their solutions and questions.

younger. Both programs served primarily low-income, bilingual Latino families.

A third program, Techbridge in Oakland, was a weekly afterschool program for girls, hosted at schools and taught by a team consisting of a classroom teacher and a Techbridge coordinator. The program supported girls' engagement in science, technology, and engineering activities and in career exploration with professional role models. Maker activities were integrated into Techbridge's robust hands-on engineering program.

The fourth organization, the Discovery Cube in Santa Ana, provided professional development to Southern California educators who wanted to integrate Making into afterschool programs housed mostly in schools serving low-income communities. The workshops were offered in collaboration with the San Bernadino Community College District.

These four organizations, along with the Explora–torium, partnering with the San Francisco Boys & Girls Clubs, worked together for three years to design and implement new Making programs and to study how to introduce Making into programs serving low-income students.

Study findings are organized into three main areas:

- How Making advanced the organizations' goals
- Key features of the Making programs
- Staff development to support productive Making programs

Advancing Afterschool Organizational Goals Through Making

Afterschool programs often see both social-emotional and academic learning as crucial to students' development and well-being. They seek to create supportive social communities in which participants can exercise choice and peer leadership. Our research has found that Making programs both contribute to and leverage such supportive communities to provide a powerful context for social-emotional and academic learning.

Encouraging Risk Taking

Making can help students to take and persist in intellectual and creative risks by allowing them to develop their ideas with the support of program staff. This process can be both challenging and rewarding.

For example, a group of Techbridge girls wanted to design and build a "progressive" alarm clock that would become increasingly loud and annoying each time the snooze button was pushed. Their design incorporated a small, low-cost microprocessor called an Arduino that they could program to raise the alarm clock's volume. The wiring and soldering in this project were complicated, and the young women had to try several different soldering techniques. In the end, they could not get the clock to work in time for the Maker Faire at which they had planned to demonstrate it. However, they remained committed to their vision and were proud of their process. At the Faire, they showcased the different soldering versions and recounted to passersby what they were trying to do, what happened, and what they planned for next steps.

Engaging Students in STEM Practices

Making engages students in authentic STEM practices, such as designing, building, testing, and refining objects based on feedback. For example, at the Fresno Community Science Workshop, students made an annual summer field trip to a nearby lake. A group of girls wanted to build a boat for the field trip. They worked together to design a six-foot catamaran that could keep two people afloat. They constructed it using PVC pipes and copious amounts of duct tape, testing different ways to wrap the duct tape (in tiles, in layers, or in a weave) to see which was the strongest and most waterproof. They also had to test how to brace the catamaran. In the end, they brought the boat to the lake and took turns taking their peers for a ride.

Developing 21st Century Skills

Making supports the development of 21st century skills, such as problem solving and critical thinking, that have been shown to advance deep learning (National Research Council, 2012a). For example, a Techbridge student wanted to hack a pair of earbuds to use the Bluetooth function to power a speaker sewn into her backpack. Engineering, testing, and trouble-shooting the system took weeks. The young woman engaged in ongoing problem solving by experimenting with the earbuds, taking them apart, and learning how the Bluetooth controls functioned. Using the earbuds' Bluetooth buttons to call her friend through her cell phone, she observed whether sound was passing through the speaker. This experiment enabled her to figure out the inner workings of the system so she could use it in her backpack project.

> Creating a "what-if" culture communicates that there are questions worth asking, concepts worth discovering—and that the process of coming to understand is a valued activity.

Expanding Young People's Vision for the Future

The programs we studied regularly framed Making as a way to improve the world through science and engineering. Making can thus expand participants' understanding of possible futures by showing how they can use STEM to contribute to their communities. For example, Techbridge staff challenged participants to develop projects for a social purpose that they could showcase at Maker Faire. The results included shoes for the visually impaired that would vibrate when approaching objects, as well as backpacks and alarm clocks that could assist teenagers with their everyday needs. Mentors working in STEM fields visited the program to help with these Maker Faire projects, offering perspectives on how STEM is used and valued in academic and work contexts.

Characteristics of Productive Making Programs

Developing a culture of exploration and creative risk taking is a critical feature of productive afterschool Making programs. Programs that are organized around asking "what if?" set the stage for creative inquiry; they can also help students persist in troubleshooting as they run into challenges. Creating a "what-if" culture communicates that there are questions worth asking, concepts worth discovering—and that the process of coming to understand is a valued activity. It also suggests that there is not a known endpoint, and that participants will learn how to do things as they engage in the process of doing them. The features of productive and equitable Making programs are outlined below.

Environments Organized to Foster Collaborative Learning

Productive Making programs make ideas, questions, and strategies visible. The tools are accessible and the horizons open, allowing everyone to see everyone else's work. Adults model processes of questioning, testing, and making. Regular reflective conversations support a community ethos of investigation. Both the physical and the social environment support collaboration.

In Watsonville Environmental Science Workshop, the organization of physical space—such as gluing stations, machine tools, and flat surfaces for building—encouraged students to engage with one another while integrating common tools and techniques into their distinct projects. For example, when an Exploratorium researcher who was building a car went to use the gluing station, she started a conversation with a girl who was using the gluing station to build a doll house. This conversation led the two to collaborate on a car for a doll.

In all of the sites we studied, facilitators roamed throughout the physical space, engaging in conversation and providing technical assistance. Like the researcher who was constructing a car, they modeled productive Making by building alongside the students. In interviews, facilitators stressed key pedagogical moves—such as asking questions and being careful not to take over projects—that could support learners. They emphasized the importance of maintaining a focus on process over perfect final products.

Process-Oriented Facilitation

Process-oriented teaching encourages careful listening and questioning; it helps learners engage in evidence-based reflection through iterative design-redesign activities. For example, at an afterschool program in Southern California, students were struggling with wiring batteries. The facilitator, building on models from Discovery Cube professional development, wrote on the board, "Failure is not the end of the process; it's just a *step* in the process." She encouraged students to share their varied approaches to wiring batteries, stressing that there was no single way to succeed.

Such process-oriented facilitation was evident across all four sites. The emphasis on process was reinforced by the fact that projects sometimes took several days or weeks to complete. Process-oriented teaching and learning means that youth work on their own ideas at their own pace, a characteristic that may be more common in afterschool than in school settings.

Multiple Entry Points and Pathways

Maker activities that are designed with multiple entry points and pathways allow students to choose their own directions based on their prior experiences and interests. For example, at the Watsonville Environmental Science Workshop, students developed individualized Rube Goldberg chain reaction machines, which they would later take to school as class projects. Each machine performed several different actions in order to move a rubber ball from the start of the machine to the end. One student started her machine by building a pinball plunger; another designed a pulley that would bring the ball to the top of a track; yet a third started his machine with a ramp.

At Techbridge, girls visited local thrift stores to choose inexpensive items that they could "hack" and repurpose. They created a Harry Potter book that screamed when turned to a page where evil character Voldemort appears, music boxes, lamps made of photographic slides, and a piggy bank whose bellybutton lit up when a coin was added. In all cases, they started with a creative idea. Then they took their thrift-store items apart; combined multiple items; and coded and integrated small microprocessors wired to lights, speakers, or sensors. Comparing these results to those of the previous year, program leaders said that students were far less likely to be frustrated when things didn't work and were more positive about the experience generally when they were allowed to select their own projects.

Connections Across Settings

The afterschool Making programs we studied linked Making activities to engineering practices and professionals and provided tools with which young people could create school projects. These practices helped the youth connect their experiences across school, home, and afterschool contexts. For example, students at the Watsonville Environmental Science Workshop regularly used the workshop to repair their bikes. Often they worked side by side with adult family members who were using workshop tools for authentic family projects, such as building a dog house or a wooden tortilla press. Students also used the workshop to complete classroom projects, such as a middle school assignment to build a trebuchet or a Rube Goldberg machine. The workshop provided tools, social networks, and space that could help young people use their design and building skills to complete their school assignments.

Staff Development to Support Productive STEM-Rich Making

All four participating organizations prioritized the professional learning of program facilitators. In particular, organizational leaders were attuned to building facilitators' capacity to provide equity-oriented Making activities. The group defined "equity-oriented" Making activities as ones in which all young people were invited and supported to participate fully. Often this meant helping students to recognize their own prior experiences and skills, positioning them as capable and knowledgeable in Making, and supporting them to persist through difficulties. Among the programs we studied, staff development to support this kind of facilitation was characterized by specific kinds of activities.

Learning to Create a Culture of Risk Taking

In equity-oriented staff development, participants experience ways to create a culture of inquiry and creative risk taking through a set of routines designed to develop trust and collaboration among students.

For example, educators from both Fresno Community Science Workshop and Watsonville Environmental Science Workshop took part in a workshop that included role-playing activities where they could experience firsthand what it would mean to be a new student unfamiliar with Making or, in one group, a facilitator unfamiliar with the kinds of support students need to get started. Using *teatro* techniques developed by Boal (2006), small groups developed short skits in which they explored the problem and improvised solutions. After their initial skits surfaced the problems and conflicts, the whole group discussed how the actions of skit participants could have better supported the new learner. They then revised and replayed their skits, demonstrating key moves that could better support a productive culture of inquiry and risk taking. Workshop participants also articulated what they valued in their work and what they valued for students, thereby building a deeper understanding of why it was important to them to support learning through Making.

For example, students at the Watsonville Environmental Science Workshop regularly used the workshop to repair their bikes. Often they worked side by side with adult family members who were using workshop tools for authentic family projects, such as building a dog house or a wooden tortilla press.

were paired so that returning educators collaborated with new educators. During activities, program facilitators were encouraged to look at one another's projects and offer support or advice. These processes were repeated in the afterschool program, where educators regularly encouraged girls to turn to more expert peers for guidance as they built their projects and paired new Techbridge students with returning students who could show them, for example, how to solder wires together safely. Peer mentoring also occurred informally. For example, when a group of girls encountered problems in programming Lilypad, a small computer used for sewing e-textiles, they had already grown so used to peer coaching that they asked girls who had used this device the previous year rather than the adult facilitator.

Experiencing Firsthand the Iterative Nature of Making

Staff of all programs attended workshops where they engaged in the very Making activities that their students would later do. In such workshops, participants reflected on how leaders had supported them to persist in the design-redesign process in a way that deepened their learning. For example, workshop leaders asked "what if?" rather than telling participants what to do. They provided tools or materials when participants needed them and not before. Throughout, leaders supported group reflection and meaning making.

For example, at Discovery Cube teacher workshops, the leader modeled ways to support learner inquiry without providing solutions too quickly. When a participant asked for help in making her circuit board work, the leader pointed her to the different models the group had already examined. He then engaged her in dialogue as she identified the positive and negative parts of her circuit. She tested her connections, rearranged wires following one of the models, and came to recognize, through this iterative process, that she had created an open circuit. On her third attempt, she successfully got the bulb to light up.

Exploring How to Position Students as Leaders

Staff development throughout the network focused on enabling facilitators to encourage students to serve as mentors, coaches, and leaders for other students. While engaging in the hands-on Making activities they would soon teach to their students, educators were encouraged to collaborate as peer leaders in the same ways they were expected to facilitate youth collaboration in their afterschool programs. For example, at Techbridge, program facilitators

Discussing Marginalization

Explicit discussions about how students might experience marginalization or deficit views in school and in society made facilitators more conscious of how to avoid reproducing these views in the afterschool program. For example, in Techbridge professional development workshops, educators discussed career access and unequal pay between men and women. They discussed the best ways to talk about such issues so that girls wouldn't be discouraged from pursuing competitive careers and salaries. Participants also addressed how people perceive intelligence and when individuals feel "smart." They discussed ways that youth could feel that their intelligence is not valued—especially when they are faced with external measures of intelligence such as standardized testing—and how to avoid replicating these experiences in afterschool.

Where We Go From Here

A 2014 review of the literature found a growing number of studies celebrating the potential power and excitement of the Maker movement in education (Vossoughi & Bevan, 2014). Most of these studies address implementation of activities, such as e-textiles or engineering; some explore the nature of Maker communities of practice. Only in the last year or so has research begun to emerge that addresses core issues of teaching and learning or the ways in which Making can be positioned to empower learners from economically and racially marginalized communities (Vossoughi et al., 2016).

The results of our study contribute to the literature by demonstrating the ways in which Making can support valued STEM learning outcomes. It also addresses a gap in professional development, which often focuses exclusively on how to implement activities. Though educators must have first-hand experience doing the Making activities they will later facilitate with students, our study suggests that this experience is only the beginning. To support equitable Making programs, educators need to learn together how to create a culture that leverages the potential of Making to engage students in the full scope of STEM practices. A "what-if" culture recognizes and builds on what students know and can do. It supports process and iterative design, helping students to persist through difficulties and imagine new solutions. It intentionally fosters reflection and meaning making.

Developing such a culture is not easy. It may require not only expert facilitation but also implementation support. For example, enlisting high school students to serve as co-facilitators can lower student-teacher ratios to allow the responsive facilitation that our research shows is critical to productive and equitable learning through Making. The challenges are compounded by high staff turnover rates in afterschool; many of the educators in the four featured organizations have since moved on. Partnerships with community Makers or science education institutions with Maker expertise may be crucial to long-term success.

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