Electronic Textiles as Disruptive Designs: Supporting and Challenging Maker Activities in Schools

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Electronic textiles are a part of the increasingly popular maker movement that champions existing do-it-yourself activities. As making activities broaden from Maker Faires and fabrication spaces in children's museums, science centers, and community organizations to school classrooms, they provide new opportunities for learning while challenging many current conventions of schooling. In this article, authors Yasmin Kafai, Deborah Fields, and Kristin Searle consider one disruptive area of making: electronic textiles. The authors examine high school students' experiences making e-textile designs across three workshops that took place over the course of a school year and discuss individual students' experiences making e-textiles in the context of broader findings regarding themes of transparency, aesthetics, and gender. They also examine the role of e-textiles as both an opportunity for, and challenge in, breaking down traditional barriers to computing.

> We may say most aptly that the Analytical Engine weaves algebraic patterns just as the Jacquard loom weaves flowers and leaves.
>
> —*Ada Lovelace, "Sketch of the Analytical Engine invented by Charles Babbage Esq." (1843)*

In May 2011 fourteen-year-old Tamieka[1] attended a four-week workshop in which she made an electronic textile in the form of a light-up, felt flower to give as Mother's Day present. Instead of a bouquet of flowers, Tamieka wanted

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to make a flower that would forever bloom—rather, forever light up—as a gift for her mother.

Before participating in the workshop, Tamieka, a young African American in her first year of high school, had no interest or experience in the fields of engineering or computing. Yet designing circuits and writing code to make an electronic textile flower helped her see connections between these fields—just like computer pioneer Ada Lovelace's observations connected computing algebraic patterns with weaving flowers in textiles more than 150 years ago. Created as part of Tamieka's ninth-grade electronic textile workshop, the flower consisted of eleven red felt petals with a red LED light on the tip of each petal, a delicate stem, and one small leaf with two green LED lights—all of which was controlled by a small, round computer that she had programmed to make the lights fade in and out in a slow, undulating pattern (see image 1).

To create this ever-blooming electronic textile flower, Tamieka had to design a functional circuit blueprint using pencil and paper, craft the flower using felt materials, stitch the circuits to connect the LED lights, and write the code to control them. She utilized sewing skills that she learned from her grandmother—indeed, she sought help from her grandmother when she took the project home one night—and drew on other skills, such as designing circuits and programming code learned in her school workshops. Making an electronic textile became an unexpected and rich context in which she learned about and developed an appreciation for engineering and computing—fields she knew little about before. The workshop also served as an entry to more traditional computer courses; a year later Tamieka applied for and attended a high school computing summer camp at a local university.

Electronic textiles, or e-textiles, are part of a growing group of maker activities that can reveal how digital media are made *and* designed, combining the physical and digital (Buechley, Peppler, Eisenberg, & Kafai, 2013). While "making" encompasses everything from woodworking and auto repair to cooking and mixing cocktails, it predominantly features the use of computational tools—both hardware and software—that have become increasingly affordable and accessible to the general public (Frauenfelder, 2010; Gauntlett, 2011). E-textiles use electronics and computing; however, they also challenge current making conventions by integrating the use of "soft" textile materials that are sewn and embroidered with conductive thread. In a comparison of individuals purchasing and making projects with the LilyPad Arduino sewable microcontroller (small computer) versus the technologically identical Arduino microcontroller, a strong correspondence was found between an individual's gender and her or his product preference. Buechley and Hill (2010) argue that this correlation is likely because the sewable, round LilyPad Arduino lends itself to textile and painting projects favored by women and girls, whereas the rectangular Arduino requires wire and solder and is better suited to other kinds of more traditional computing or engineering projects (like building a robot) that typically attract men and boys. The challenge of getting more women

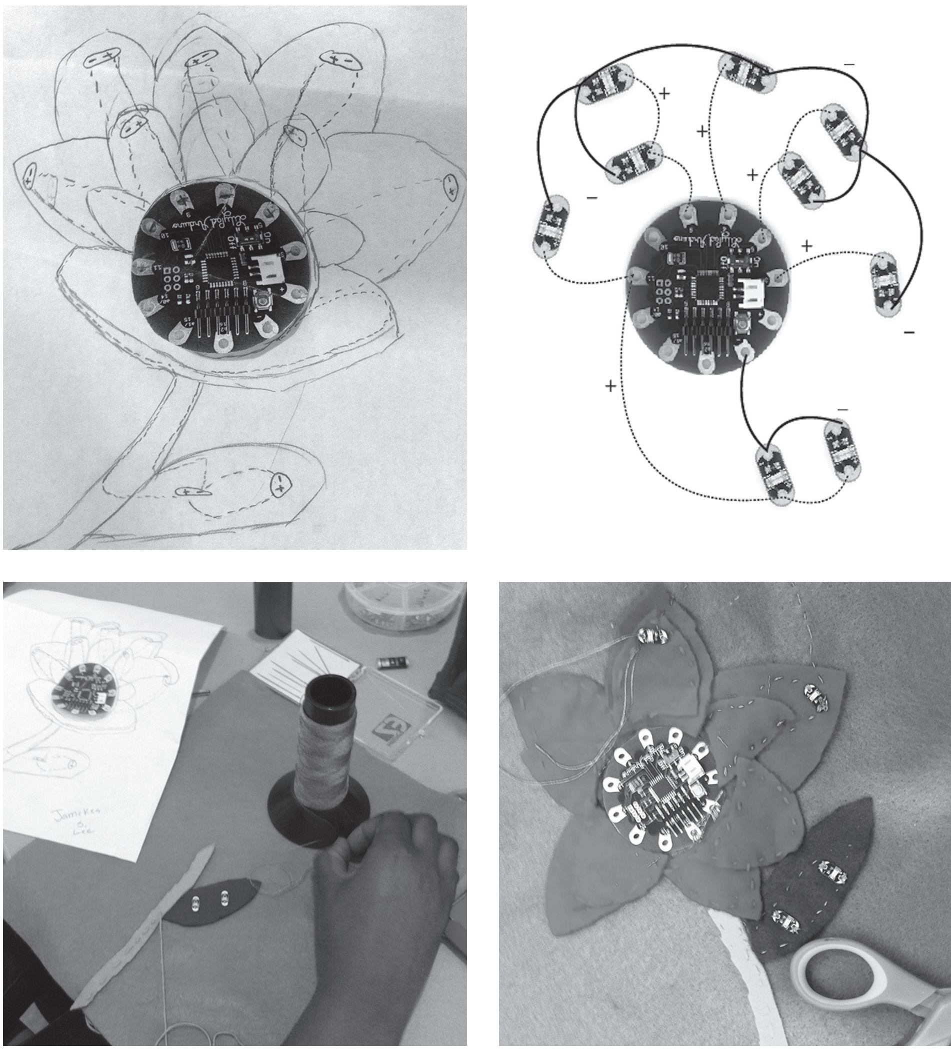

Image 1. *Tamieka's initial blueprint design (upper left), our drawing of her circuit schematic (upper right), her design and e-textile sewing in progress (lower left), and the almost-complete e-textile flower (lower right). Photographs copyright © Kristin A. Searle*

involved is important to all STEM fields (Ong, Wright, Espinosa, & Orfield, 2011) but is particularly poignant in computing, which some have called a "locked clubhouse" because it seems to be open to mainly boys and men (Margolis & Fisher, 2002; Margolis, Estrella, Goode, & Nao, 2008).

In this article we examine high school students' experiences making e-textile designs across three workshops that took place over the course of a school year. Students had the opportunity to participate in up to three workshops that each lasted for a minimum of eight hours, with projects growing in complexity during the year. To analyze students' engagement and learning, we focused on the following research questions: How does designing with e-textile materials promote transparency of technology, a better understanding of how technology works? What role do aesthetic considerations play in students' making of e-textiles? And in what ways do e-textile activities complicate students' gendered perspectives on computing and engineering? Our study is based on an examination of students' design processes and final e-textile products, observations of workshop activities and conversations, and debriefing interviews conducted with students at the end of each workshop.

Throughout this article we discuss individual students' experiences making e-textiles in the context of broader findings regarding themes of transparency, aesthetics, and gender that come into play when making with e-textiles. Indeed, we argue that the co-presence of these themes are key to e-textiles' success in opening doors to students traditionally excluded from technical domains. The hands-on fabrication of e-textiles is paired with the learning of decidedly more (at least as popularly perceived) minds-on computing and engineering. The combination of academic skills and hands-on work is a much-needed but missing facet of current schooling (Rose, 2005). In light of this, we also examine the challenges and opportunities of bringing e-textiles into schools.

Background

E-textiles are a part of the "maker movement," increasingly popular among educators and policy makers (Honey & Kanter, 2013), that champions existing do-it-yourself (DIY) activities, particularly those that include a digital component. E-textiles, like Tamieka's flower, incorporate elements of engineering and computing by using sensors for measuring light, temperature, and pressure and "actuators" such as lights that are sewn with conductive thread on clothing and attached to small, flat, sewable computers (microcontrollers) that can be programmed (Buechley, 2006). As making activities spread from Maker Faires (large events that showcase DIY creations) and fabrication spaces in children's museums, science centers, and community organizations to school classrooms, they provide new opportunities for learning but also challenge many of the current conventions of schooling (Honey & Kanter, 2013). Bringing maker activities like e-textiles into schools disrupts the notion of "right" answers and the ideal of achievement codified on uniform standardized tests that have become such a visible part of today's schooling (Kliebard, 1995). Instead, making prioritizes students' desires and abilities to invent solutions to custom needs, debug problems that arise from their own initiative, and understand how technology works (Dougherty, 2013).

While the concept of disruption is typically associated with promoting school reform (Christensen, Horn, & Johnson, 2010), here we focus on three critical themes—promoting transparency, integrating aesthetics, and increasing diversity in learning with e-textiles—that serve to disrupt typical notions about *how* and *who* can and should learn and create with computers. These three themes may appear unrelated at first, but we strategically address each in turn to argue for their mutually beneficial importance. Each of these themes interdependently influences the others. The pairing of crafting with circuitry and programming—all historically gendered technologies (Ensmenger, 2010)—plays a key role in making computing transparent, facilitating functional aesthetics that support learning, and supporting new visions for participation across traditionally gendered boundaries.

Technological Transparency

To begin, we consider *transparency* in technology learning. The concept of transparency may initially seem counterintuitive since computers are now visible everywhere, particularly outside of school (Ito et al., 2009). However, few youth engage deeply in creating with technologies or begin to understand what makes the technology work, how it is put together, and who can and should participate in designs (e.g., Hargittai, 2010). Most computer classes offered in schools focus on getting students to use applications—from simple presentation software and word processing to more complex data collection, analysis, and simulation—rather than produce them (e.g., Collins & Halverson, 2009). These technology classes promote an understanding of computers and software as black boxes where the inner workings are hidden to users.

In contrast, working with e-textiles gives students the opportunity to grapple with the messiness of technology; taking things apart, putting them back together, and experimenting with the purposes and functions of technology make computers accessible to students (Resnick, Berg, & Eisenberg, 2000). When students like Tamieka design e-textile flowers, they begin to understand the technological components and functionalities that are behind the shiny cases of their devices. In other words, by engaging learners in designing e-textiles, educators can encourage student agency in problem solving and designing with technologies. This work can disrupt the trend that puts students on the sidelines as consumers rather than producers of technology (see also Buechley, 2010). Students must take up active roles in which they decide what needs to be created, how to create it, and how to make it work through the many challenges and practicalities of the design process.

Integration of Aesthetics

Our second theme, integrating *aesthetics* as a part of learning, foregrounds factors other than functionality—or making things work—that are meaningful to students' learning. Engineering and technology fields often ignore aesthetics, appearing to be purely factual and objective rather than the innately human enterprises they really are (Lemke, 2010). Yet, aesthetics have long been an intrinsic part of many STEM fields (Girod, 2007). Even Dewey (1980) promoted aesthetics in education as transformative in helping people reenvision the status quo and challenge traditional structures of society. Likewise, Vygotsky (2004) argued that developing a mastery of technology must accompany an expression of creative imagination—learning cannot be separated from and can indeed be enhanced by artistry and aesthetics. Despite this, aesthetics are little applied in schools today. At best, aesthetics are included purely in the hopes of motivating or engaging students or, as a Trojan horse, to interest students in technology (Blikstein, 2013) but not to further their academic learning (e.g., Brickhouse, Lowery, & Schultz, 2000).

However, the creation of e-textiles includes an explicit acknowledgment of aesthetics in technical design. When Tamieka designed her e-textile flower, she attended to how her project looked and functioned and, in the process, delved deeper into learning about circuitry, programming, and crafting. It is through this customization and attention to the overall process of creating an e-textile project that aesthetics can play a role in learning as well as engagement. Students must develop the skills and technical knowledge necessary to express themselves in any medium, whether it involves more traditional media (clay, paint, pastels) or new media (computers, conductive thread, LEDs), an argument that also has been made by proponents of arts education (Groff, 2013). In this way, students' aesthetic and creative expression must accompany and be accompanied by the technical learning as well, leading to a consideration of the synergistic relationship between technological transparency and functional aesthetics.

Diversifying Computing Fields

There has been a notable absence of women and minorities in computing in the past thirty years (e.g., Cohoon & Aspray, 2006). These trends should not be surprising given that few students ever encounter computer science at any point in their K–12 education. Further, in the few U.S. high schools that offer an Advanced Placement (AP) course in computer science (only 5 percent nationwide), women and minorities represent less than 20 percent of AP test takers (College Board, 2013). Most attempts to broaden participation in computing have focused on "unlocking the clubhouse" of computer science in schools (Margolis & Fisher, 2002), with robotic construction activities being the most popular example (Bers, 2012). While robotics competitions are popular, they have not been successful in recruiting girls (Melchior, Cohen, Cutter, & Leavitt, 2008–2009). The maker movement has also been criticized for overemphasizing projects like robots and drones and featuring primarily white male creators in their magazines (Buechley, 2013).

The development of the LilyPad Arduino (Buechley, 2006) addresses some of these concerns. It includes sewable microcontrollers, sensors, and actuators that can be used to teach programming and engineering concepts. Because LilyPad has made e-textiles accessible to novice designers and draws on multiple domains that are traditionally gendered but relate to different groups, it provides a new venue for engaging students. In our society, textile crafting, such as sewing, embroidery, crochet, and knitting, is traditionally considered a feminine or "soft" (Parker, 2011) activity, while engineering and computing are considered masculine or "hard" (Oldenziel, 1999). While e-textile construction kits are similar in many functional aspects to robotics construction kits, e-textile kits use soft materials rather than motors and gears and incorporate crafting techniques. E-textiles have been shown successful in reaching out to new makers. In a study of LilyPad Arduino users (hobbyists) posting projects on the Web, Buechley and Hill (2010) found that a far higher percentage of women use the LilyPad Arduino than the technologically identical Arduino. While the Arduino is rectangular in shape and combined with other components using wire and solder, the LilyPad Arduino has a circular shape, and components are sewn together using conductive thread. This suggests that a culturally hybrid construction kit, one that combines different materials (e.g., a circuit board and cloth) and techniques from different traditions (e.g., sewing, programming), can indeed attract different groups while still functionally engaging them in the same technical complexities and challenging their preconceptions about what computing is, what applications it can have, and who has expertise to do it.

In this article we attend to each of these themes in turn while considering the relationship between them throughout. Doing so allows us to unpack separately the importance and legitimacy of transparency, aesthetics, and gender before reflecting on their complementary influences on students' learning and engagement with e-textiles. We focus first on how making with e-textiles can promote greater *transparency* of engineering and computing. This maker activity, like many others, is rooted in constructionist pedagogy (Papert, 1991), in which students take on responsibility as designers rather than as consumers of technology. Having students create technology runs contrary to longstanding educational practices that favor learning how to use applications (Kafai & Burke, 2014). We then examine students' personal *aesthetics* as a key element in creative making. Most school artifacts such as homework and worksheets are valued solely for their functional demonstration of learning technology—getting the right solution is what is important. We illustrate how e-textile maker activities can instead foreground aesthetics, thereby improving students' designs and also contributing to their deeper engagement with electrical and computing concepts. Finally, we seek opportunities to break down barriers to computing by changing students' *perspectives* on what is possible with computers and to whom they are accessible. We argue that e-textiles provide this opportunity through integrating the "high" masculine technologies of engineering and computing with the arguably "low" feminine technologies of crafting and sewing (Faulkner, 2000; Parker, 2011). By combining these historically gendered domains in unexpected ways that simultaneously connect personal aesthetics with technical learning through transparency, e-textile making disrupts students' notions of what can be made and who can participate in technology fields.

Context of E-Textile Class, Students, and Data Collection and Analysis

Designing and Implementing E-Textile Classes

The e-textiles class we explore here was composed of three workshops that took place in the context of a public magnet high school focused on science and technology in a large urban school district in the Mid-Atlantic region. Over the course of one school year, thirty-five freshmen, ages fourteen to fifteen, participated in the workshops. The students' self-identified demographic composition was 23 percent African American, 29 percent Caucasian, 14 percent Asian, and 17 percent mixed race/ethnicity. Five students opted to not identify their race/ethnicity in survey responses. Just under half of the participants were girls (n = 15). Overall, the racial and gender demographics of the class reflected the diversity found in the school and district at large. In spite of students' interest in science and technology (as indicated by their choice to apply to this particular magnet school), only a few of them had any prior programming experience, and none had ever worked with electronic textiles when they elected to participate in the e-textiles class.

The e-textile workshops were offered to students as part of a partnership between the high school and a local science museum. The museum hosted activities for all ninth graders in the school in the form of semiformal workshops that took place at the museum one afternoon a week during the school year. Students could choose between several workshops, each lasting four to six weeks, taught by museum staff or volunteers. This platform offered us, local researchers interested in bringing e-textile making activities to students, the opportunity to develop workshops for students. All of us have a background in teaching in out-of-school learning environments, and much of our collective research is focused on how to bring activities that engage youth in out-of-school spaces into the classroom environment (see Kafai & Fields, 2013). While we all had taught individual e-textile workshops, we had not used the LilyPad Arduino and were interested in having students work on multiple, computational e-textile projects of increasing complexity so that we could better understand what they were learning and how this connected to school-based computing and engineering classes.

During each of our three workshops over four weeks, we met our students once a week for two-hour sessions in the museum space. Not all students participated in all three workshops, but participating in the third workshop required some prior experience with e-textiles. As ours were among the first workshops that engaged K–12 students in computational designs with the LilyPad Arduino (rather than simple circuits, which typically took far less time) in school-based educational settings, we had no prior models for projects to do with students. Thus, we developed and iterated on the workshop content in real time. Moreover, we were not only interested in designing and instructing an e-textile workshop; we also set out to explore how and what the students learned during the making activity. As such, we took on the roles of instructor, designer, and researcher. Our research approach used participant observation (Spradley, 1980), as we simultaneously led workshops and collected data. Fields and Searle were the primary teachers and data collectors, writing up notes every week on observations.

In the workshops students learned how to design and create their own e-textiles projects, beginning with paper-and-pencil designs, followed by drawing circuit schematics, then sewing and crafting their designs with textile materials, and finally programming the LilyPad Arduino (see image 1). In the first of the three workshops, all students were novices, and therefore the activities built more slowly on one another. Most students made basic e-textiles projects by sewing simple circuits to connect one or two LED lights and programming them to turn on and off. Roughly half of the students in the second workshop, and all but one in the third workshop, had prior experience with e-textiles. As students gained more experience making (and we gained more experience teaching), their e-textile projects increased not only in the complexity of circuit designs and programming code but also in the sophistication of crafting and sewing. Over the course of the three e-textile workshops, after twelve weeks and more than thirty-six hours, students moved from making simple, blinking designs on textile felt to more complex, wearable designs, including a hat inspired by anime symbols, a light-up tote bag with light-sensing handles, and a belt inspired by the double-helix structure of DNA (see image 2).

Documenting and Analyzing E-Textile Activities

While the descriptions of the e-textile projects and classes break down e-textile making into different processes—such as sewing, designing circuits, and writing code—in reality many of these activities overlap. We found that learning how to make circuits could not be separated from learning how to sew and write code, and vice versa. We believe that the interconnected nature of e-textiles activities challenged students the most and fostered their learning. This interconnectedness also posed particular challenges to us as we documented and analyzed students' making and learning experiences in absence of any established measures and instruments that could provide benchmarks of achievement. We thus opted for a documentation process that included video recordings of groups to capture their conversations and activities as well as photographs of their projects in various stages. We complemented these data with daily field notes and interviews we conducted with each of the students at the end of workshop. In the interviews, we asked participants to discuss their e-textile projects and to reflect on activities and experiences in the workshop, such as why they chose to make a particular design, whether they made any changes in their project as they moved through various making stages, what the best part of making the project was, and what the hardest or most frustrating part was. For each question, we asked students to recall a particular

Image 2. *Students' final e-textile designs: a Jack Skellington patch with light-up eyes decorates a backpack (upper left); a tote bag with light-sensing handles (upper right); a wearable belt with a double-helix (lower left); and an anime-inspired hat (lower right). Photographs copyright © Kristin A. Searle*

instance or to tell us a story, such as, "Can you tell me a story about what it felt like when you got the lights on your project to turn on for the first time?"

Making sense of and connecting these different data sources was an equally complex process. For this article we selected several students to illustrate the complex and intertwining themes of transparency, aesthetics, and gender. These themes emerged emically from the data and were developed only after substantial, systematic analyses of designs and activities in each workshop. As a first step of data analyses, we logged all video recordings of group interactions; we summarized the activities occurring on screen in a minute-by-minute written document and transcribed all interviews. We then conducted a two-step open coding (Charmaz, 2000) of all our data (field notes, logged videos, and transcribed interviews). We began by reading a third of the data and listing some of the challenges of learning to design with e-textiles. Then we created an initial coding scheme of the learning challenges—the moments where students struggled with getting their projects to work—categorized by the overlap of crafting, circuitry, and coding. Since we were relatively new to teaching with e-textiles, we did not know what things students would grapple with and used these moments to see what they learned. One example of such a challenge became embodied in a code we called "the back is as important as the front." When learning to sew, one is usually taught that it is okay for the back to be messy. However, when sewing with uninsulated conductive thread, a messy back can lead to short circuits and a project that does not light up. Through documentation of learning challenges, we identified this as one of the things students struggled with and later succeeded in learning.

We analytically coded one section of the data together to build consensus and proceeded to independently analytically code one workshop each. Through a combination of informal analytic memos written to one another and repeated group discussions of insights gleaned from the sections that we coded independently, we refined our coding scheme to reflect insights from this analysis of the data and then recoded all the workshops. We created a thesaurus of codes with definitions and examples and indexed (i.e., counted) all codes, listing them by date with a one-sentence summary. This allowed us to see which learning challenges were most prominent in individual workshops or across workshops, if and how those challenges related to aesthetics, and what role gender played in students' perspectives on e-textiles. Our overall coding approach focused on how students designed and redesigned their e-textiles to make them functional and wearable. The changes and breakdowns in this redesign process became a productive lens for understanding how students improved in their comprehension of circuit designs and programming language. In other words, we were able to document students' growing understanding of how technology works.

After completing this broad analysis, we developed portfolios on the sixteen students who participated in the third workshop to see how individuals' design trajectories related to the prevalent themes of transparency, aesthetics, and gender elicited in the broader coding. We conducted "backwards and forwards mapping" (Putney, Green, Dixon, Duran, & Yeager, 2000) tracing chronological developments in the students' work. Specifically, we began with one design decision and then traced it backward to the circumstances that led to it and then forward to the consequences of it. We compared these maps to students' own reflections on the design process as expressed in interviews. This process allowed us to compare students' progress horizontally (between students across the classes) and vertically (within each student over time) for a fuller picture of what they learned, why they made specific design decisions, and how this mattered for them personally.

Findings: Learning by Making with E-Textiles

Inside the Black Box: Encouraging Transparency with E-Textiles

Making e-textiles renders visible the basics of how computers and electronics work (Kafai, Fields, & Searle, 2013). As the students we observed began to attach individual lights to textiles, they came to learn that sewing circuits is more similar to connecting them with wires or alligator clips (the tools traditionally used to craft lighting circuits) than it is to sewing a button onto a shirt. Many students began by sewing on the lights as if they were buttons, taking the conductive thread and sewing straight through both sides. However, lights have different properties than buttons, and in order to direct electricity through the lights, students eventually learned that they must cut and tie knots on each end of the thread to direct electricity through the light to turn it on. This principle often eluded students when they connected circuits using alligator clips, even if they were able to create a functional circuit. But in sewing the circuit, the principle of forcing electricity through a light to make it light up became clearer because they had to choose to cut thread to create that electric pathway. When working with alligator clips, one rarely has to consciously cut a wire. Similarly, loose threads on the back can short a circuit when uninsulated threads with a positive charge and threads with a negative charge accidentally touch. Again, when using alligator clips, one rarely has to worry about uninsulated wires touching each other because the alligator clips are generally insulated with rubber or plastic coating.

Tamieka created multiple drawings and layouts of her project as she learned how to design circuits. She progressed through several increasingly technical iterations before she had an adequate design that fulfilled both her aesthetic and technical visions. Then she had to sew it, a process that took several days and much help from her friends, her teachers, and her grandmother. Indeed, Tamieka asserted that the most difficult part of the project involved planning and sewing the circuits, "trying not to cross the positive and the negatives . . . to keep checking back and forth." She explained how she had to keep looking between her circuit blueprint and her sewn e-textile so that she knew which part went where and how the positive and negative threads were connected so that she did not accidentally put things in the wrong place. Overcoming challenges like learning to avoid wire crossing changed the way Tamieka thought about engineering and computing. Like other students in the workshop series, she talked about how her project made her knowledgeable and interested in electronics in a way she had not been before. She even came in during a special lunch session to learn how to use programming features such as variables, conditionals, and nested loops to make the lights fade in and out. Her participation in this session resulted in new computing knowledge that was integrated into her e-textile flower design and into her sense of being someone capable of programming. Her grandmother declared the project "pretty good," her friends raved about it, and Tamieka herself saw the flower as "my first thing, like my first big project, something I, uh, . . . accomplished, and I'll give it to [my mom] so, like, so she can hold it for me." Making e-textiles incited Tamieka's budding interest in computing.

Tamieka's experiences are illustrative of our broader findings about learning and the increased transparency of computers for the students who attended the e-textile workshops (see Kafai et al., 2013). We found that the infusion of crafting into the domains of electronics and code made the inner workings of circuits and programming more transparent. In the process, students began to realize how complex computers are and yet at the same time found them more approachable. In the end, John, an African American with an interest in programming, expressed his new respect for computing: "I didn't know it took all this to light stuff up." Similarly, Marcela, a white female of European descent, commented that learning to program with e-textiles was much less intimidating and much easier to understand than her experiences with other programming languages. Through overcoming challenges, identifying problems, and generating solutions, students felt a sense of learning, accomplishment, and even control over the computer. They became makers.

Because creating e-textiles involves knowledge in multiple domains, this type of making introduces challenges that are particularly needed in schools. Rather than single right answers, the kinds of challenges encountered in e-textiles encourage identifying the nature of a problem out of many possibilities, considering a number of viable solutions, and choosing the best alternative. For instance, when Tamieka struggled with mapping back and forth between her circuitry blueprint and her e-textile artifact to avoid crossing wires, she had already chosen from a number of possible solutions, including insulating the conductive thread with a felt patch or a piece of tape to allow for crossed wires or simply wiring in such a way as to avoid crossed wires, even if it meant more sewing. Other students had to problem-solve when they plugged their project into a computer for the first time and programmed it to make the lights turn on. A light that did not work might be the result of a coding problem (forgetting to tell the computer to turn the light on) or a myriad of possible circuitry problems. Students had to toggle back and forth between the computer screen and the project itself until they could diagnose and fix the problem to make the light work. Indeed, Sullivan (2008) argues that solving these types of design problems helps learners develop intricate inquiry skills, such as how to engage in an iterative feedback loop of observation, testing, and evaluation of solutions. The physical components of designing and crafting circuits enables a transparency that facilitates engagement with and learning of programming. Important to this process is the understanding that the crafting cannot be pulled apart from learning about circuits and programming; these three components are closely intertwined. In this interconnected and interdisciplinary context, crafting and aesthetics are not simply add-ons to an otherwise technology-based activity; instead, crafting and sewing become an inextricable part of designing and programming electrical circuits. This interconnectedness becomes more important in discussions of the roles of aesthetics and gender in students' e-textile experiences.

Beyond Functionality: Highlighting Aesthetics in E-Textile Designs

We discovered the importance of aesthetics the hard way. In the beginning we prioritized functionality as the key aspect of students' designs. It was most important to us that the lights worked and that students found some success in the engineering and computational aspects of their projects. Yet, in the end, students who followed our suggestion to make the simplest working designs did not even want to keep them, finding them unattractive and having little personal ownership over them. In contrast, students who went beyond our original suggestions and incorporated artistic and attractive elements in their designs, not only felt more ownership of their work but also created more challenging projects for themselves. In subsequent classes we began to foreground aesthetics by encouraging students to make drawings of what they wanted their project to look like before they understood all of the components that would make them work. Of course, students had to redo their drawings multiple times in order to incorporate the necessary elements of circuits and to allow for the greatest flexibility of programming. In this process of redesigning on paper and on fabric, students faced more complex challenges and were also more motivated to solve them to realize the desired appearance, activity, and interactivity (i.e., aspects of the aesthetics) in their projects. In the final class, we traced the design process of every single student and found that attending to the aesthetics in their projects motivated the richest learning, which was embodied in design alterations they made in the process of reaching their aims (Fields, Kafai, and Searle, 2012).

To illustrate this process we introduce Amari, a fourteen-year-old, Southeast Asian girl who was placed in the second e-textiles workshop against her choice but who eventually enrolled in the final e-textile workshop of her own accord. In the beginning, Amari thought the class would be too "techie" for her. However, when she saw that some of the primary materials were felt and thread, she began to feel more comfortable:

> The first day I thought that it'd be really confusing and I wouldn't like it and I'd just be sitting there like, "Oh, God" . . . But when I saw that they were just cutting felt, I was like, "Oh, I can. Oh, this is probably easy."

Though she had no prior experience with sewing, the low-tech nature of the craft materials and techniques (like cutting) made them seem more accessible. She began by cutting a star out of white felt, sewing it onto a pink felt circle, and tentatively considering where to put the lights. She later reflected, "I just sewed it onto felt and then I was like, 'It's time for lights and techie stuff,' and then slowly I started to understand it." She decided to put five lights on the points of the star and began to draw her design for how they would connect to power sources and the LilyPad computer (see image 3). At first she just put little dots for lights at each tip of the star, but with feedback from the teachers she drew in her blueprint the needed circuitry connections to the lights—after all, they would not light up without a power source. She quickly realized that the design was becoming too complex with too many lines of thread. This led her to consolidate all the negative connections to the lights into a single line, or a common ground, that she traced around the outside of her star, forming a circle. Amari proceeded to sew the lights to the LilyPad

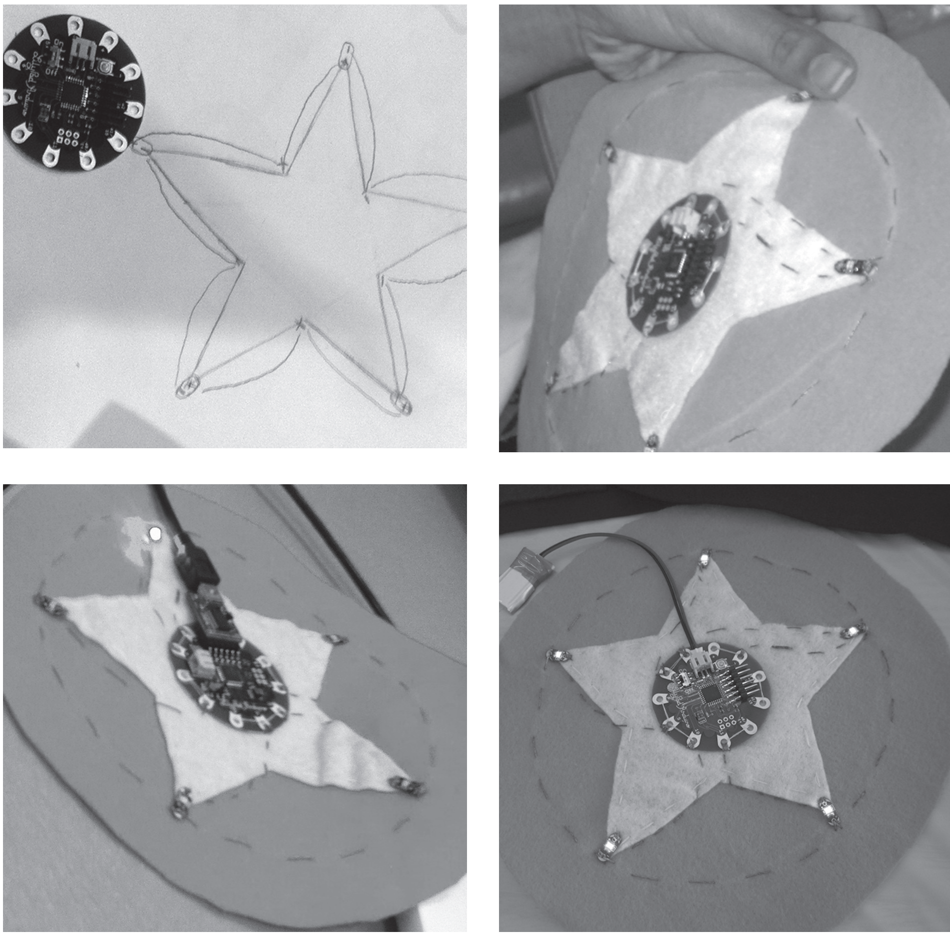

Image 3. *Four iterations of Amari's design process. Photographs copyright © Kristin A. Searle*

with carefully orchestrated swirls, then debugged her project (trimming the back) until every light turned on.

Amari, like all students enrolled in the final workshop, included more sophisticated circuitry in her project because of her desire for particular aesthetics. Similarly, ten of the sixteen students sought additional instruction on programming outside of class in order to design and program more complex effects in their lighting. Making something both aesthetically pleasing and functional became a space of creative tension that promoted learning (Fields et al., 2012). We noted that the inclusion of aesthetics played a crucial role in students' learning because students became deeply invested in their projects (as opposed to the simple, mostly throwaway projects made in the first workshop) and were intrinsically motivated to learn more complex ways of doing things in order to achieve their desired aesthetics. This finding is particularly critical as schools have struggled to connect STEM learning activities to students' personal interests and everyday lives (e.g., Barton, Tan, & Rivet, 2008; Nasir & Hand, 2008). We suggest that other STEM fields might benefit from these insights about aesthetics and learning by encouraging personal expression and customization in student projects in ways that are authentically integrated with a particular STEM discipline, and by developing new kinds of activities that support students' ownership and connection with STEM (Buechley & Hill, 2010; Eglash, Gilbert, & Foster, 2013). This connectedness also played a role in changing the participants' perceptions about who can engage with STEM.

Beyond Robotics: Opening New Clubhouses of Computing

E-textile maker activities also have the potential to diversify students' perspectives on who can and should participate in crafting, computing, and engineering. We found that many students had preconceived notions about the fields in which they and their peers would be most capable; their ideas seemed to be based on cultural norms about traditionally masculine and feminine tasks (see Kafai & Peppler, 2014). The boys often talked about themselves as good at the coding and circuitry aspects of e-textiles, whether or not they had any prior experience in these areas in practice. Likewise, many of the girls, like Amari, positioned themselves as more comfortable with crafting, whether or not they had any prior experience sewing or crafting. In this way, students' ideas of a "girls' domain" and a "boys' domain" were heavily gendered and influenced how they approached e-textiles, irrespective of prior experience. However, by the end of the workshops, some of these norms had begun to shift: most boys were proudest of completing the physical crafting task (e.g., sewing), while most girls became proudest of the coding achievements in their projects. Repeatedly, girls in particular reflected that they were initially worried about the techie elements of e-textiles but then learned what they needed to learn, mitigating their initial concern.

Consider Kyra, an African American ninth grader who, like Tamieka and Amari, initially did not see herself as confident or capable of programming her project. This, however, changed after she spent some time crafting her project and after she became interested in learning about coding and circuitry. Kyra was able to pinpoint the exact moment—as she connected the light on her pink heart (see image 4) with conductive thread and programmed it to blink—when she went from being less comfortable to more comfortable with the computing aspects of e-textiles: "At that point, I just felt like, 'This feels good—because I know how to do this.' And I felt kinda like an expert . . . I'm proudest that it actually blinks."

For Kyra and others, making a functioning project was a significant achievement. Not surprisingly, the elements that felt like the biggest accomplishments

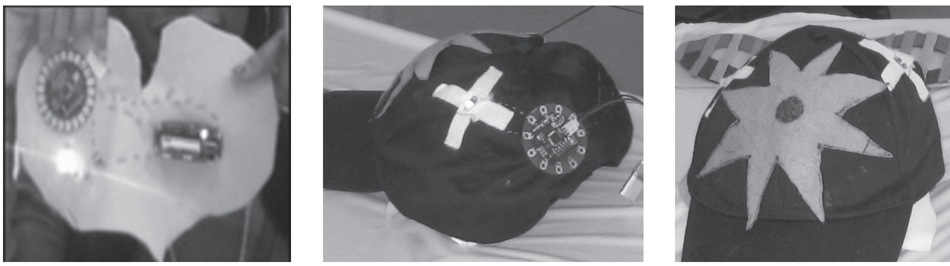

Image 4. *Kyra's e-textile heart (left) and Lucas's anime hat (center and right). Photographs copyright © Kristin A. Searle*

were also the elements from which students initially felt most distanced. When asked about the most frustrating part of making her e-textile artifact, Kyra discussed her experiences coding:

> Because, at first, I didn't know what to do. I was just like, "Coding? What do you mean coding?" . . . But then, after awhile, it was just, "Ok, this is easy. I get it. Just type in this and type in that. Make this do that." So, like, you are the controller. You make it do what you want it to do.

Kyra began to take on more of a techie and expert identity by developing a better understanding of what programming is—telling the computer exactly what to do and in what order. She was always capable, but she lacked confidence in the beginning. While not all of the girls in our study were as comfortable as Kyra with taking on this identity, almost all of them expressed satisfaction at knowing about circuitry and how to write computer code. Many girls' perspectives changed simply through having the opportunity to learn about something technical and to do so through a medium (i.e., crafting and sewing) that felt comfortable to them. This process made visible the inner workings of computing and allowed for ample personal aesthetics.

In contrast to Kyra and most girls in our study, many of the boys tended to see sewing as a means to an end—a skill they used to complete the techie stuff, often reiterating stereotypes about sewing and gender. Early on, Lucas, a white student, proclaimed sewing to be "a girl's sport." In the first workshop he sought every possible opportunity to avoid it and engaged instead in programming in a language not applicable to e-textile projects. When we suggested that e-textiles could be equally interesting and fun, he replied, "Oh yeah? Sticking yourself with a needle is really fun." For his first project he attempted to make a hat but failed because the stiff backing of the hat made sewing difficult. In the second workshop he returned to the hat but focused instead on applying an anime-inspired design (see image 4). Lucas's aesthetically motivated persistence with the e-textile project is worth noting because, as he stated, "mainly I really don't create stuff physically, but I like to do stuff on the computer." Yet he was most proud of the yellow star he had cut out from a sheet of felt and affixed to his hat using iron-on transfer paper. Lucas also reconsidered his thoughts on sewing as a girls' "sport" when he reflected on the idea of creating circuitry by sewing. As he told us in the debriefing interview after his last class, "I think it's a[n] odd experience, considering I'd never actually think that a thing that I thought was a woman's sport until now would actually be a pretty fun thing." This change in attitude toward sewing is illustrative of Lucas's and other boys' altered perspectives on what can qualify as a masculine activity, an important element of challenging hegemonic notions of masculinity and of making space for students' multiple identities (Hull, Kenney, Marple, & Forsman-Schneider, 2006; McCready, 2010; Pascoe, 2007). Perhaps even more importantly, both boys and girls developed a new appreciation of how difficult sewing crafts were, thereby shaping a new awareness of the expertise required for this type of activity.

In the end, many students struggled with reconciling their own conflicting notions of gender in the activities involved in making e-textiles. Patrick, an African American student, summed up his experience in e-textile design:

> I like the fact that you can use programming and sewing all together, because it's kind of a weird mix. It's like hot sauce and ice cream at the same time. It's like, you'd never think the two came together. It's kind of cool.

It is this "weird mix" of crafting, circuitry, and programming in functionally aesthetic ways that makes e-textiles a compelling context for bringing this particular maker activity into schools. Patrick's comment, and those of the other participants, illustrates that while students are shifting their ideas about who can do crafting and computing tasks, the persistent cultural framing of these two tasks as different from each other suggests that their gendered understanding of the computing and crafting has not faded away entirely. Students can learn the kinds of design-based technical skills that they would learn when engaging in robotics or 3-D printing, but they do so in a potentially more critical (perhaps even disruptive) way that forces them (and us) to reexamine our taken-for-granted, gendered notions of who can do which tasks well and what it means to do those very tasks (Kafai, Lee, et al., 2014). These discussions around the gendering of technology are important because they bring preconceived notions related to gender out into the open, even if they are not completely reconciled. This is an important first step if we want to open the clubhouse to those traditionally excluded—in this case, women—and at the same time create new clubhouses that promote more diverse computing activities, like e-textiles.

Discussion

Maker activities like e-textiles promote the idea of students as designers and creators of technology. Because e-textiles combine the seemingly disparate domains of crafting, engineering, and computing, designing with e-textiles foregrounds important questions about who is involved in making and what is being made. Not only does the act of creating e-textiles help make technology more transparent by revealing what underpins the design and construction of circuits and programming of lights, but the activity also demonstrates the importance of aesthetics in learning. The relevance of aesthetics in learning is recognized by educational theorists such as Dewey (1980) and Vygotsky (2004) but is little recognized in schooling in general, and even less so in technology or engineering education. E-textiles also provide a promising venue for revealing, and beginning to break down, multiple barriers to participating in computing for some students, young women as well as young men. The experiences of Tamieka, Amari, Lucas, Kyra, and many other students demonstrate the ways that creating e-textiles can provide rich opportunities to create aesthetic designs that challenge students' gendered notions of making with computer technologies.

Challenges to Integrating E-Textile Activities in Schools

One unique aspect of our research on e-textiles is that we conducted these activities as part of the students' traditional school day, rather than in afterschool or out-of-school contexts (e.g., Peppler & Glosson, 2012). Introducing e-textile activities, like any new curricular activity, into schools is a complex enterprise that brings with it the inherent challenges of changing the status quo. Yet bringing these activities into schools can help make them accessible to a wider population, including to students like Amari, who may not choose to engage in them of their own initiative. We hope that our documentation of students' learning through e-textiles will encourage opportunities like this in other schools that serve to disrupt notions of what, how, and who is learning with technology.

In our case, we have been able to create these opportunities for high school students in short-term electives, first in a series of three, month-long elective workshops for freshmen, as reported here, then later in a quarter-long computer science elective class (Kafai, Lee, et al., 2014), and most recently in a university special topics course (Fields & King, 2014; Lee & Fields, 2013). These electives provided us with the freedom to structure learning projects that were student driven, allowing aesthetics to play a prominent role in design. Because we were the teachers, we were able to implement a students-as-designers model in the classes. In addition, the students came from a school where project-based learning was the norm. In other situations, implementing a students-as-designers model might be more difficult to attain. Searle, for instance, has recently been collaborating with a Native Studies teacher in an American Indian community, and students' e-textile designs have been constrained to themes that the Native Studies teacher is already covering in class, even if students are not especially invested in these themes. A prescribed curriculum, an extremely limited time period, or even students who are unaccustomed to project-based learning are a few of the potential obstacles to implementing a students-as-designers model in other contexts.

Challenges to authentically integrating technologies into education are not new. Since the 1920s the adoption of new educational technologies—from film to radio to instructional television—have faced the same implementation issues (Cuban, 1986). The reception of each new technology went through a similar cycle of excitement, implementation, disillusionment, and blame. Cuban rightfully predicted that the latest educational technology, computers, would follow this same cycle. What is to stop e-textiles (and the maker movement in general) from following down this same path? In more recent work, Cuban (2013) argues that the key to change lies not in the adoption of a new technology but, rather, in the development of an alternative view of students and teachers. Viewing students as problem solvers and inquirers and teachers as coaches, guides, and prodders requires a shift in educational practice and policy. In other words, our views of students, teachers, and the role of the technology in education are as important as the technology itself.

Challenges to Disruptive Designs for Learning

One of our key arguments is that e-textiles can help increase the participation of historically marginalized groups—particularly girls and women—in computing. This is important because despite the popularity of digital media with youth, on the whole, very few children are using their devices—be it a laptop, iPad, iPhone, or Droid—for more than mass consumption of commercial media (Kafai & Burke, 2014); and those who do are typically white, affluent males, highlighting disparities by traditional gender, ethnic, and class divides (Kafai et al., 2013). E-textiles bring a welcome change to this situation by making technology designs transparent and by illustrating in more accessible terms what lies behind the shiny screens that encase many personal and mobile technologies popular with youth. Although there are other kinds of maker activities that also engage students in creative designs, such as robotics or video game designs, they often reproduce common digital divides of gender, race, and class (see Melchior et al., 2008–2009). In contrast, e-textiles have the potential to challenge traditional models of clubhouses of computing by creating a culturally and epistemologically distinct model that, based on our and others' research, is more inclusive for the underrepresented populations in computing that need it most (Kafai, Searle, Martinez, & Brayboy, 2014).

However, it is also important to acknowledge that e-textiles can exploit, change, or reinforce gendered notions of aesthetics and technology. For example, we capitalized on the girls' (culturally gendered) initial affinity for crafting as the entry point to computing. In addition, the student reflections illustrate that gender norms continue to persist, even if girls feel more aligned with technical aspects and boys feel more appreciative of crafting aspects of e-textiles. In our study, the girls showed greater transitions than the boys by developing new identities as "techies." While most boys, like Lucas, certainly found new appreciation for more femininely characterized crafts like sewing, the activity did not necessarily open up new identities for them with the same magnitude as it did for the girls. Perhaps one explanation for the greater change in girls is the existing power dynamic that privileges scientific and technical knowledge over crafting knowledge. Gaining knowledge from and aligning with more masculinized domains, especially computer science, may have led to buy-in from the girls. Thus, the juxtaposition of contradictory activities, such as crafting and computing in e-textiles, might help students see their distinct gendered nature while at the same time unintentionally reinforce the very differences the activity was intended to eradicate. It is worth considering whether the very notion of disruption may, in practice, reify what it is intended to change. However, we suggest that, at least in this case, the disruptive e-textiles opened up new venues for discussion and the opportunity to question traditional norms.

Introducing Hands-on with Minds-on Activities

By valuing crafts as a relevant domain of expertise, e-textiles challenge and disrupt dominant stereotypes of what kind of knowledge is academically valuable. We see this as a chance to celebrate work done with our hands, whether primarily in the crafting domain or other hands-on work traditionally undervalued. Over the past fifty years there has been a trend in the field of education toward valuing abstraction rather than concrete work, manifested in part in the denigration of vocational classes like shop and home economics (Rose, 2005). Rose (2012) traces the roots of the prioritization of the abstract over concrete in Western society all the way back to Plato and Aristotle, with their devaluing of common craftsmen and artisans. Bringing maker activities to schools allows us to highlight the importance of the hand to the activities of the mind. Doing so might help educators rethink the learning process.

E-textile activities respect both hands-on problem solving and practical design, as well as more minds-on algorithms and abstract concepts. They also elevate handcrafts traditionally pushed to the side as women's work done at home. In sum, e-textiles provide opportunities for students and educators to revalue the cognitive work done by using one's hands (Rose, 2005). This is often the same craftwork performed by students' families and passed down through generations. These kinds of connections between school and home have been found essential in creating bridges between different funds of knowledge available in communities (Moll & Gonzalez, 2004) and for valuing the expertise that students and their families can bring to school (Fields, 2010).

Tamieka connected with her grandmother by showing her e-textiles, and other students in our study often remarked on how their projects became the centerpiece of family dinner conversation. In nondominant communities, parent involvement in schools is often lacking because schools have a history of discriminatory practices; and, especially in the era of high-stakes testing, students often feel very disconnected from their families' lives (Lareau & Horvat, 1999). E-textiles may be one way to reverse that trend, with school becoming increasingly more relevant to the kinds of work students *and* their families do outside of school. E-textiles can also point the way toward other activities that value traditional home and hand skills—woodworking, painting, scrapbooking, cooking, and others, as far as one can imagine—and may find new value through creative integration with digital technologies.

Conclusion

Maker activities like e-textiles illustrate that it is important to involve students in creating in two distinct modalities of learning: the digital and the material. Learning content and skills need to involve new domains that broaden contexts and perceptions of technological designs. E-textiles are one type of hybrid activity that combines the digital and material in authentic, aesthetic ways and can draw diverse groups of youth into identification with disciplines by connecting seemingly abstract computing and concrete, hands-on, do-it-yourself craft.

E-textiles reintroduce a historical link between computing, engineering, and traditionally women-led crafting that has been lost in today's curriculum with its overemphasis on academics. The Analytical Engine, a nineteenth-century general-purpose computer conceived (but never actually completed) by mathematician Charles Babbage, was based on the design of the mechanical Jacquard loom for weaving fashionable complex textiles of the times. But it was Ada Lovelace (1843), Babbage's aristocratic colleague, who wrote what is considered the first computer program for that conceptual computer and linked together textiles and computing. E-textiles provide a way for Lovelace's pioneering spirit to return to the field of education. Her innovations are born anew in students' designs that light up, change colors, and play music.

Note

1. All student names are pseudonyms.

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