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A rubric for describing competences in the areas of circuitry, computation, and crafting after a course using e-textiles

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A rubric for describing competences in the areas of circuitry, computation, and crafting after a course using e-textiles

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Abstract

Purpose – In light of growing interest in the maker movement and electronic textiles (e-textiles) as an educational technology, the purpose of this paper is to characterize competence change in undergraduate students who participated in a semester-length course that used e-textiles.

Design/methodology/approach – This qualitative and exploratory research study used semi-structured pre- and post-interviews with undergraduate students ($N = 7$) thinking aloud through novel tasks in order to understand their learning from a semester-long course involving e-textiles. This design was intended to elicit student thinking with commercial toys that differed from the types of projects they had completed in their course. A coding scheme was developed and organized into an analytical rubric to map depth of understanding in the three spheres of circuitry, computation, and crafting. Select cases of pre-post change were identified to illustrate growth in specific content spheres.

Findings – Students' ability to reason through novel tasks showed growth in each sphere, provided that the student did not begin with a full level of sophistication in a particular area during the pre-interview. Although students may not reach normative or expert-like competence, there are demonstrable indications of growth for each of the dimensions.

Originality/value – As e-textiles are increasingly turned to educationally, the creation and presentation of a rubric for describing competence in three spheres, especially the previously understudied area of crafting knowledge in e-textiles, is itself a useful contribution to the field. This is also an extension of e-textiles learning research into undergraduate instruction, an as-yet understudied setting for maker education.

Keywords Assessment, Arduino, E-textiles, Electronic textiles, Lilypad, Maker movement

Paper type Research paper

Introduction

For several decades, the idea of having students work through the process of creating new digital artifacts has been seen as a powerful approach for supporting learning. Seymour Papert (1980) published his seminal book, *Mindstorms*, advocating a vision of the child as simultaneous builder of public digital artifacts and knowledge of mathematics and computing. Under the umbrella of constructionism, this vision of children as computational learners and producers has been extended in a number of software development environments (e.g. Resnick *et al.*, 2009).

More recently, a resurgence of interest in the idea of students learning by creating digital artifacts has occurred, this time with physical construction happening alongside digital production. Associated with what many call the "maker" or "DIY" (do-it-yourself) movement (e.g. Blikstein, 2013; Knobel and Lankshear, 2010), this constructionist comeback represents an important contemporary direction in the field of educational technology.

This maker movement has largely drawn attention to the production of artifacts like robots or drones created with computers, wires, and soldering. But this has been gradually changing, in part due to the development of new microcontrollers and components that can

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cross boundaries with respect to what materials are used. As an example, the LilyPad Arduino microcontroller (Buechley, 2006, 2013) was designed to easily attach to fabric and other soft, malleable materials using conductive thread rather than wires for connections. Microcontroller boards like the LilyPad lend themselves to the creation of electronic textiles, or "e-textiles."

As e-textiles have seen increasing adoption and appeal to people of many backgrounds, the task ahead for educational technologists is to characterize what learning takes place with their use. Some work has been done to demonstrate that learning of specific content happens with e-textiles. However, tools and rubrics for characterizing learning along predicted trajectories are still lacking. This paper offers and illustrates a rubric that others can build upon and adapt as more efforts begin to assess and describe e-textile-based learning.

Literature review

Research on learning with e-textiles is still emerging. An early qualitative study on e-textiles asserted that completing e-textiles projects helped students develop competences in circuitry, computing, and crafting: the three areas where students often encountered difficulties (Kafai *et al.*, 2014). Those three areas were inherently intertwined. For instance, sewing conductive material results in learning beyond traditional circuitry knowledge because it involves sewing circuit topologies with uninsulated thread where ill-placed threads can create short circuits. Programming sewable LED behavior further requires different considerations than standard event-based programming in a screen-based programming environment because one must consider the physical layout of the circuits and the varying numerical ranges of hand-crafted sensors. However, the findings from Kafai *et al.*, were only suggestive. Degrees of learning in circuitry, computing, and crafting had not been articulated nor specified.

More toward the direction of specification, some systematic and quantitative analyses of e-textiles learning focused on learning gains related to circuitry. Peppler and Glosson (2013) assessed student knowledge of simple, series, and parallel circuits in e-textiles through scored pre-post design tasks administered in a youth afterschool program. They found significant gains in students' ability to diagram working circuits and in their understanding of current flow, polarity, and connection as a result of working with e-textiles. A classroom study using questions from established standardized tests on circuitry also found significant gains pre-post in student knowledge when working with introductory e-textiles (Tofel-Grehl *et al.*, 2017). Another classroom-based study developed slightly more advanced measures to study student understanding of computational (programmable) e-textiles circuits, such as measures of students' ability to read related Arduino code (Litts *et al.*, 2017). This study similarly found significant improvement in students' performance. However, by design, these tests only focused on circuitry and tasks that matched the original domain where e-textiles were learned or on standardized test items. Transfer to applied activities, such as new kinds of artifacts and DIY projects, had not been established.

Two research studies have begun to investigate whether students can solve new problems through concrete debugging or "deconstruction kit" tasks. Fields *et al.* (2016) developed actual e-textiles project with intentional malfunctions and studied pairs of students as they solved those problems. Similar efforts have focused more simply on examining students debugging e-textile code without an accompanying physical project (e.g. Kafai *et al.*, 2014). In both cases, assessment has focused on items similar to those that matched training conditions and ignored the role of crafting as an element of e-textiles learning.

While transfer of knowledge is notoriously challenging (Bransford and Schwartz, 1999), we have thus far little documentation of how working with e-textiles might enable students to think about issues of circuitry, computation, and especially craft in tasks that less directly match training conditions. Ideally, e-textiles experiences could bring about new capabilities for learners. For instance, can someone refine their ways of seeing and noticing (Goodwin, 1994; Stevens and Hall, 1998) such that newly developed knowledge from e-textiles related to circuitry, computation, or craft knowledge might be applied? Would they gain new insight into how interactive technologies worked? To examine that, we designed an exploratory study that intentionally used tasks and objects to elicit student thinking that were not based on LilyPad Arduino technology. By performing a grounded analysis of the resultant interview data, we developed the rubric that appears and is illustrated below.

Instructional context

This instructional context was a new university level educational technology tool course described in Fields and Lee (2016). Open to both graduate and undergraduate students at a large public university in the Western USA. The enrollment for the course was 20 (12 undergraduate students, eight graduate students. Over the semester, students completed a series of five semi-structured mini-projects which exposed them to a range of capabilities and possibilities with e-textiles. These included making a bracelet that would light up when worn, a fabric object that could sense and respond to human touch, another fabric object that could respond to some other environmental change (such as stretching or bending of material), a video game controller using unconventional materials, and a five-note "piano" out of soft materials (see Buechley and Qiu, 2013, for the fabric piano). Finally, each student proposed and completed their own final e-textile project, such as an interactive skirt that lit up when the wearer would spin.

Methods

Given the modest size of the course's enrollment and the authors' interest in exploring the range of student ideas that would be elicited given commercial objects that differed substantially from what they had encountered in the course, a qualitative research approach was taken. While much of the existing research on learning with e-textiles was qualitative, transfer of knowledge to new contexts had not been studied. Therefore, we needed to develop a clearer specification of what were appropriate targets for student learning and identify how students' ideas in a new task context would be expressed. This was also an opportunity for us to determine which interview tasks could be more fruitful for informing the design of future quantitative assessments.

To maintain greater uniformity in age and background, we performed semi-structured interviews only with undergraduate student volunteers. The graduate students, as noted in another paper, were far more varied in age and had many more years of specialized expertise (Fields and King, 2014). Seven undergraduate students completed matched pre and post-interviews (20-45 minutes long) scheduled during the first and last week of the semester, respectively. The instructor of the course had no prior knowledge about how many or which students were participating in the study. All interviewed students were novices in computing but varied in their prior knowledge of circuitry and craft.

Data collection approach: semi-structured task interviews

Data were collected through semi-structured task interviews. These interviews involve a protocol with a set of predetermined tasks and prompts designed to elicit extended periods of student reasoning. These interviews were designed intentionally to be similar to those used in conceptual change research (diSessa, 2007; Sherin *et al.*, 2012). The appeal of open-ended conceptual change style interviewing was that they could elicit a broad set of student ideas, and their robustness can be subject to ad hoc follow up questioning.

The particular interview protocol we developed involved students explaining their understandings of how each of three commercial interactive children's toys worked (Lee and Fields, 2013). Pre and post-interviews used the same protocol and same toys, and all participants discussed all toys. One toy was a floating rubber duck that lit up when placed in water. Responses to students' explanations for how that toy worked informed the current rubric and are already discussed elsewhere (Lee and Fields, 2013) but are not included in this paper. The two toys featured in this paper include: a fabric rabbit toy that had a firm plastic button and casing inside that when pressed, would flash lights in the rabbit's ears and play a short song, and a stuffed elephant toy that was made of floppy material and had separate casings for different body parts. For the rabbit toy, the student was asked to explain what was inside of the toy that allowed it to respond with flashing lights and to draw what was inside of the toy to make it work. The music-making functionalities were not discussed in the interview. For the elephant toy, the students were told that they were to describe in detail what they would need to do in order to turn the elephant toy into one that had ears that lit up when a user touched the two upper paws simultaneously. As with the rabbit toy task, the student was also asked to produce a drawing of the inside of the elephant as well. There were no official correct answers since many solutions were possible. For example, to solve the elephant task, one could place button switches inside the elephant paws or use the human body as a conductor to complete a circuit. No use of an Arduino or any microcontroller was necessary for a proposed answer to be a reasonable solution, although some students did propose solutions using a microcontroller (Plate 1).

Rubric development

The rubric we developed was informed by an iterative analysis of the interview data. Analysis was completed in three phases. In the first phase, the first author and a student assistant conducted a pass of grounded open-coding (Charmaz, 2006) across all interviews

Note: Interactive rabbit with light up ears and stuffed elephant without any electronics components

Plate 1.
Toys used in the interview

categorizing all of the students' explanations for how the toys worked (or could be made to work, as was the case for the stuffed elephant). The second analytical phase involved reviewing and organizing the codes into emergent themes, which incidentally turned out to map onto the three content spheres described above (crafting, circuitry, and computation). This was done by the first author prior to awareness of the same proposed content scheme from Kafai *et al.* (2014) and incidentally identified by the second author. This convergence in critical content spheres was suggestive of validity of those content areas as being primary intertwined ones where knowledge would change.

Following reorganization of codes by the content spheres and consolidation of similar code categories, the first author and the student research assistant re-coded the data set. At this stage, a four-point scoring rubric for the data for each of the three spheres was developed because of variation across students despite common codes being assigned. The lowest level of the rubric described undergraduate novices in the area with no more experience than that provided on the first day of the course (when students sewed wristbands with parallel circuits and a switch). The highest level on the scoring rubric demonstrated fully meeting all the learning goals of the course in that area was exemplary of a student who could propose effective and working solutions to the toy tasks. Table I shows the resulting rubric.

For the third phase of analysis, the first author and the student assistant jointly reviewed the interviews a final time and assigned a numerical score from the rubric to students' interview responses. These assigned scores were allowed to be assigned to exact levels (e.g. 1 or 3) or in between levels (e.g. 1.5 or 3.5). Once these scores were identified and agreed upon for both pre and post-interviews, we prepared charts to show our assessment of student understanding in the three spheres and drew descriptive case comparisons within and between students.

Illustrating change in students

One key output of this study was the development of a rubric for students' circuitry, computation, and crafting knowledge as applied to how they reason about the design of practical objects. One should not take this rubric for granted. E-textiles knowledge, both as it exists prior to instruction or after a designed learning activity, has not been mapped out in depth. At best, researchers have studied and/or designed assessments to measure learning in simple and parallel circuitry (Peppler and Glosson, 2013) or with computational circuitry and basic conditional coding (Litts *et al.*, 2017; Kafai *et al.*, 2014) with students who have completed at most a single full computational circuitry project similar to the first computational project in the e-textiles university course described here. The students featured in this paper completed four additional projects beyond any other study of e-textiles that we are aware of. Further, no prior study that we know of has sought to capture expertise in crafting as it relates to e-textiles, yet we found that it was a key component of students' ability to predict or map out the design for how an electronic toy can work. This may be because of the lack of academic status given to handcrafts (see Rose, 2004). By capturing three interrelated areas of e-textiles expertise development in a rubric-scoreable manner, this study breaks new ground in understanding e-textiles expertise in breadth and depth of learning.

Additionally, students' ability to reason through the toy tasks showed growth in each sphere, provided that the student did not begin with a full level of sophistication in a particular area during the pre-interview. This is depicted for our three focal students in the three-dimensional radar plots shown in Figure 1. Stated simply, the triangles formed within this space of circuitry, crafting, and computational knowledge are larger in all of the post-interviews than those of the pre-interviews. In the entire data set of seven students, the area of these triangles changed by a factor of +1.4 to +3.6, with the larger increase being represented by the student who started out with the least developed prior understandings.

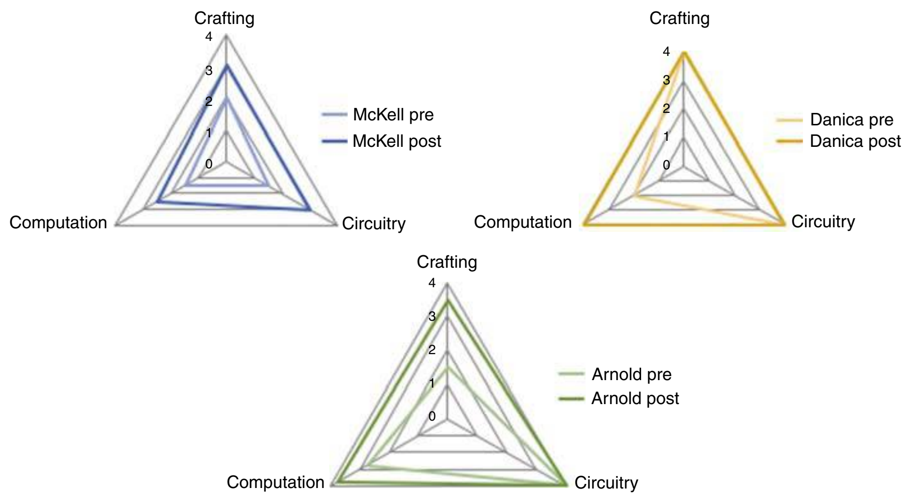
	Level 4 criteria	Level 3 criteria	Level 2 criteria	Level 1 criteria
Circuitry	Can correctly use and describe resistance and capacitance related to the objects in question Demonstrates broad awareness of the range of conductive materials and that non-conductive insulation is intended to prevent short circuits Understands that for circuits to be functional, they and the associated components must have complete connections and appropriately join positive and negative Knows how to prevent short circuits and how insulation can be used	Articulates flow of electricity and that the amount of electricity flowing can vary Can name multiple conductive materials but may attribute conductivity to incorrect properties of materials, such as already having electricity in them Articulates that for circuits to be functional, they and associated components must be completely connected or is aware of rules for connecting positive and negative Knows some heuristics for avoiding short circuits, such as keeping conductive thread from crossing	Knows how to use ground connections and ports, is unsure how electricity moves between them May mention switch without articulating it completes a circuit, knows some idiosyncratic materials that can serve as a switch Recognizes that positive and negative connections are necessary between components but may not know which connections are correct. May know that more than two components can be interconnected Knows short circuits are a problem with e-textiles	Provides an incorrect intuitive model of electricity, such as it being pushed out of a battery Is aware of some materials being conductive but cannot accurately predict which ones or why Demonstrates awareness that components of a circuit need to be connected, but sequence and closure are unspecified Knows short circuits might be a problem
Computation	Understands that computer programs are handled by a microcontroller that operates on a list of given instructions. Understands meaning behind several program specific values Understands the needs to initialize and declare ports that can be used for multiple purposes. Distinguishes between analog and digital ports Understands basic control flow including conditionals, loops, and events	Understands that computer programs are handled by a microcontroller that operates on a list of given instructions. Understands meaning behind some program specific values Understands some code preparation needed for ports to behave in certain ways Understands one or two aspects of basic control flow, such as conditional statements and loops	Knows that computer programs are like a list of prewritten instructions, some instructions are required for functionality but they do not know why Is aware that different ports can do different activities (sensing, acting) but unclear about how to prepare them Lacks articulation of logic structures but understands that code is involved. May know some specific code is necessary for some logic structures but does not understand why	May know that electronic objects are programmed but does not know what that involves and how programs are executed Is not aware of the need to initialize or make declarations, different components work in particular ways because that is how they are constructed Bases observable actions as being related strictly to immediately observable human actions but not sensors or encoded rules

(*continued*)

Table I. Rubric developed for competence in circuitry, computation, and crafting

	Level 4 criteria	Level 3 criteria	Level 2 criteria	Level 1 criteria
Crafting	Understands that seams serve to join different pieces of fabric together and are the best place to cut into an object to preserve fabric quality Predicts how a given craft is to be used in the future and can plan craft design to account for expected wear and tear Considers esthetics of the craft and ways to hide mistakes or unattractive objects or seams	Understands that seams serve to join different pieces of fabric together and are good place to cut to preserve fabric quality Knows some parts may be easier for holding components, but may not consider how craft use can affect durability and reliability of components Considers esthetics of the craft and ways to hide mistakes or unattractive objects or seams	Understands that seams join different pieces of fabric together but may not consider those necessary or appropriate for cutting Arbitrarily chooses places for components but considers size and relative locations for components when deciding on placement but placements could unintentionally be appropriate for functionality Considers esthetics loosely, typically with nice stitching and no loose components being the major concerns	May recognize that there are seams, but focuses on separating or opening fabric objects based strictly on where they want access rather than where it would be easiest or best esthetically to cut Is unaware of how movement, use, or material can affect the usability of craft object, makes no mention of those as considerations Does not mention nor consider the resulting appearance of a craft object

Table I.



Notes: McKell, top left; Arnold, top right; Danica, bottom center

Figure 1. Three dimensional radar plots showing pre and post knowledge of undergraduate students

The focus of the current paper is the rubric and its illustration in each dimension rather than describing all three areas of learning simultaneously. However, Figure 1 shows growth in multiple areas for multiple case students. To illustrate change in each content sphere, we present some brief examples and data excerpts below.

Change in circuitry knowledge

To illustrate what change in circuitry knowledge looked like within the data, we draw from interviews with McKell. McKell was an undergraduate who had almost no prior experience in crafting, circuitry or computing. A communications major, she came to the course with an interest in digital media and enrolled in the course in order to complete a required minor. During her pre-interview, McKell generated some non-normative explanations for how the toys worked. Of particular interest here is the one she provided for the interactive rabbit after she activated it and it began making music and lights flashed in its ears:

> MCKELL: Yeah, there is probably like wires that come up from his belly. The switch would be in his belly […] when you squeeze it, it pushes the power to go on and the power goes up through the wires and into the lights in the ears […] You have to push it to – to make the energy go out.

McKell inferred that there was some button that gets pressed when squeezed and then "power goes up through the wires and into the lights in the ears." Until the button was pressed, it was "stored energy" and the energy would not "go out" of storage. One has to "push it to […] make the energy go out." Of note here is that the energy flow follows a single direction. The energy simply went out from the switch to the ears, but there was no evidence of circuit completion being involved. While she mentioned a "switch," there was no evidence here or elsewhere in the interview that she thought of switches as completing circuits. Following this exchange, she was asked to produce a drawing (see Figure 2(a)) to help her explain what she was saying.

While preparing the drawing, McKell was unsure of where a battery would be located, but knew there should be one to supply energy. She ended up drawing the same battery twice as circles within the plastic casing, once next to the button (the square inside the plastic casing) and once underneath it. Of note in the drawing is the presence of single wires connecting the LEDs. In a canonical circuit drawing, there would be some wires returning to the battery to complete the circuit.

From these excerpts, McKell did not have an immediately accessible nor robust understanding of some core ideas related to electrical circuits. Her description and drawings

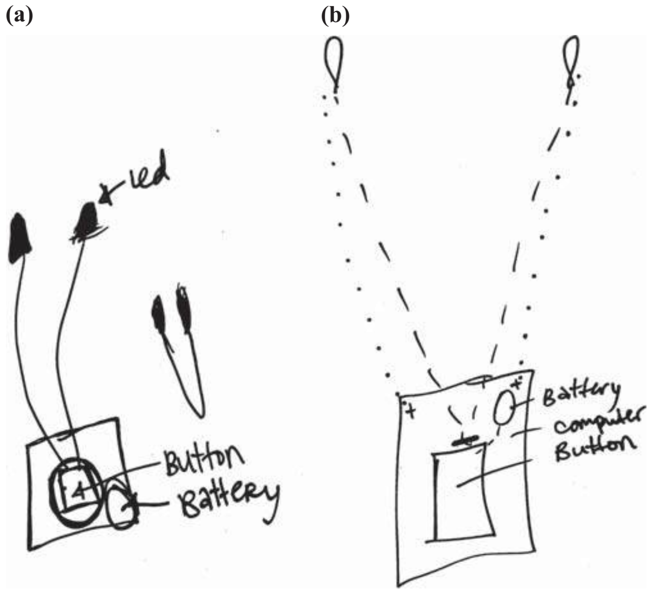


Figure 2.
McKell's drawing of the internals of the interactive rabbit toy during her pre-interview (left) and her post-interview (right)

for how components and a power source were connected were inaccurate, and it was not apparent that she could articulate the way in which a physical event, such as a button push, could complete a circuit. She did, however, recognize the importance of some components, such as batteries, wire, a switch, and LEDs, that were involved.

During her post interview, when given the same task, McKell showed marked improvements. She did not have a fully normative understanding, but she did incorporate some more accurate ideas related to circuits and how they worked. For instance, she made an explicit note about positive and negative connections to loop wire through the LEDs and back to a "computer" (or microprocessing board). This was shown in a drawing that she produced (see Figure 2(b)). Furthermore, she mentioned a button that would turn on lights when pushed. When asked how the button worked, she described it as two pieces of metal that must come into contact with one another, very close to an accurate and full description of a button switch. In her post interview, she did not mention "pushing" energy out of the battery despite several related questions to elicit that idea from her again.

This way of talking about circuits being completed and connected to a power source appeared throughout McKell's post interview. Because there was some occasional imprecision in her language (at one point, she talked about circuits leading to a reaction and conductive materials containing electricity within them), we did not see McKell as having full mastery of circuitry content. Yet it was clear that she had moved further into this space than where she had originally began (from levels 1.5- 3) and could see the same problem in a different way than before.

Change in computational knowledge

To illustrate change in computational knowledge, we present an excerpt from Danica. A nontraditional undergraduate student studying art who was quite knowledgeable about craftwork across physical media due to her major, Danica could produce sophisticated craft solutions in response to our questions. She also was married to an electrical engineering student and had previously gained a lot of familiarity with circuitry informally. Thus she scored at the highest levels in the pre-interviews for crafting and circuitry (level 4). However, computational knowledge, in the form of articulating procedures and algorithms was new for her. There was no mention of these topics in her initial explanation of how to work the elephant. When asked to draw a picture, she created the drawing in Figure 3(a). This figure looks more like a circuit diagram than any other student's drawing in the pre-interviews and even includes a resistor and some conventions for showing positive and

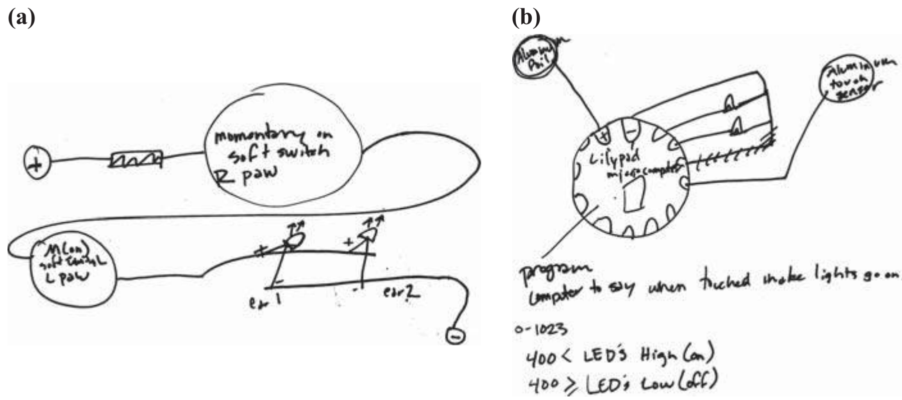


Figure 3.
Danica's drawing of the components and connections inside the elephant during her pre-interview (left) and her post-interview (right)

negative connections. However, when she was asked about programming, she remained vague and said somehow toys that had programming had some instructions to make them work the way that they did.

In contrast, during her post-interview she expressed new ideas about how programming could be involved. She drew a new circuit diagram that this time included a LilyPad microcontroller and capacitive touch sensors (see Figure 3(b)). Then she articulated some of the rules that she would program into the system such that when both sensor patches were touched, the lights would turn on. She began to write out an approximation of the conditions she would use complete with a binary range of readings (from 0 to 1,023) that the sensor would produce as well as several conditional expressions using “ $<$ ” and “ $\geqslant$ ” signs in ways that match Arduino programming code (Figure 3(b)).

These were unsolicited, and if anything may be limited in that the approximated code she produced was Arduino specific. As that was one of her first encounters with a programming language, it is not surprising that she relied on it for values. However, it is possible that with more exposure, she could offer code that was less platform specific or involved other values and commands. Still, we observed that this was a substantial change (Level 2 to Level 4) from someone who had no prior programming experience of her own. We had kept in some contact with this student and learned that following the course, she then went on to independently pursue some novel interactive art projects for her final undergraduate art exhibition, including using a programmable heart rate sensor to create rhythmic flashing lights in an etched glass heart-shaped art piece.

Change in crafting knowledge

As stated above, one especially compelling feature of electronic textiles is the connections that they provide to craft culture. Crafting can take a number of forms but has been robust enough and so central to cultures that crafted artifacts become important exhibit pieces in museums, and in some countries, there are large chain stores and companies dedicated exclusively to the distribution of crafting products (e.g. *Michael’s* in the USA). However, craft knowledge is often passed down informally, such as through family and in extracurricular activities during one’s childhood (e.g. Fields and King, 2014). Courses related to craftwork do not typically maintain a major presence in the computing and technology curriculum, particularly in the USA where the current study took place. Still, by virtue of the technologies used and the course design, some students who had little to no explicit craft experience were able to show improvement in that area as well. Some studies with youth who worked with e-textiles have included self-reports from students that among their most noteworthy accomplishments was their relative improvement in sewing capability (e.g. Searle and Kafai, 2015). However, no e-textiles study to date has offered a systematic way to characterize change in crafting knowledge.

To illustrate our characterization of craft-related knowledge change, we present excerpts from the elephant portion of the pre- and post-interviews with Arnold. Arnold was an undergraduate majoring in journalism who felt very comfortable with circuitry since he liked to repair cars but was relatively unfamiliar with computing and working with soft crafts like textiles. The latter was especially clear in his pre-interview when he discussed how he would make it so that the stuffed elephant’s ears would light up when its paws were touched. In particular, he mentioned that he would cut the elephant open, gesturing down the front and center of the elephant, which was already a single piece of material. When other students with more craft knowledge were asked about this, they would instead move the elephant around and identify seams in the elephant that they could cut and then repair so that they did not create the need for new seams and to maintain the original toy’s appearance. Another detail that some more experienced crafters noticed is the filler material that is used. Different fillers have different properties and can unintentionally conduct electricity or damage components (such as bead filling). The elephant had three different filler materials that could be felt upon handling. In his pre-interview, Arnold made no acknowledgment of the fillers despite handling the toy and being given prompts.

In his post interview, it became evident that Arnold had become more aware of some better textile craft practices. To illustrate, consider the excerpt below when he was asked again about how to make the elephant's ears light up when a user touches the paws:

> Arnold: so ideally what you want to do is open this up and put a small zipper here <*points to back seam on toy*> so you can open it up and also get to a processing board to program it as well. So you could crack it open here <*points to vertical and horizontal seam in back of toy*>, open up the sides really, fold it open and place all your wires, you can probably poke the wire through here <*points to elephant's right arm*> and the thread, poke it out here, do all your programming, zip it up, and you wouldn't see it until the next time you open it up to recharge it […] You could almost unfold this whole thing here. Unstitch that <*points to horizontal seam*>, unstitch this <*points to vertical seam*> and then it is just <*squeezes elephant's body and pauses*> stuffing inside and place all your components and wire it up.

Of note is his immediate consideration is that he made the electronic components accessible. His proposal was to have a zipper in the back of the elephant. This led to him saying he would "open up the sides really, fold it open" and place wires inside of the elephant. The benefit to having this rear opening and zipper would be that "you wouldn't see it until the next time you open it up to recharge it." This suggests that he was more considerate of the esthetics and spatial construction of the elephant toy after he considering his enhancements, making electrical components hidden but still accessible.

When talking about how he could "crack it open" so that he could "open up the sides," he happened to motion directly over the main seams. In the pre-interview, Arnold had suggested an arbitrary cut in the front of the elephant. Yet in the post, he thought of existing seams as desirable places to cut or "unstitch". He also paused to squeeze the elephant and appraise what kind of filling ("stuffing") was inside, suggesting more consideration of materials that could be in contact with the added components.

In summary, Arnold came into the course knowing a fair amount about circuitry but was unmindful about how to physically analyze and manipulate (through seams) the elephant toy. Given the same task after the course, he showed improvement (levels 1-3.5). Arnold left far more attentive about using seams as entries, maintaining the toy's appearance, creating access to added electrical components through a zipper opening, and verifying that the material in the toy would be appropriate to hold his proposed components.

Discussion

E-textiles present an emerging opportunity for educational technologists to study learning by making. To make a functional e-textiles project, one must consider the kinds of materials used, the techniques of connecting them (e.g. sewing), the physical layout (topology) of the circuits, and the coding of sensors in relation to user interaction with the resultant fabric artifact. Although prior studies documented significant learning in pre-post tests of basic circuitry and simple reading of code, our study delves more deeply into the degree of competence change in a semester-long e-textiles university course. In particular, the rubric and analysis we developed attends to crafting, an area that while acknowledged as important (Kafai *et al.*, 2014; Searle and Kafai, 2015), was entirely missing from any previous attempts at assessment, and to novel tasks that were outside of the users' direct experience in that they analyzed interactive toys that used different technology and were commercially produced rather than replicas of what students had already encountered in instruction.

Thus our rubric provides a detailed way to begin to map learning in different areas of e-textile design than those examined before.

Because this rubric was developed from student interviews within the situated context of a specific e-textiles course where students made a particular set of projects, it is not universal. However, we believe it can provide a starting point for investigations of other e-textiles learning environments, such as those beginning to reach into *K*12 classrooms where assessments are being developed (e.g. Tofel-Grehl *et al.*, 2017; Litts *et al.*, 2017). Future research could contribute by documenting a range of trajectories in younger students (i.e. *K*12), connecting e-textiles knowledge to disciplinary knowledge such as science or computer science as some are beginning to explore (e.g. Tofel-Grehl *et al.*, 2017; Fields *et al.*, 2017), and exploring the roles different types of projects play in directing students' learning by making.

The current study is limited in that it drew from a small population and was intentionally exploratory. However, as e-textiles become more common as a form of educational technology, it is important that initial efforts to develop methods of assessment and describing change in competence be developed. Over time, the early products can be adapted and improved for eventual larger-scale use.

In closing, we have sought to demonstrate – with a new task context and population – that the intuitions about learning through making e-textiles do indeed have more empirical support. We hope that both the analytical scheme and the demonstrative cases of growth here are useful for informing future research, design, and assessment around e-textiles as an educational technology.

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