

Making teachers: Expanding physics teacher education

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Grounded in constructionist learning theory, Maker education facilitates knowledge building through the construction of personally meaningful physical artifacts. Maker education has shown potential to promote learning, engagement, identity development, and interest in science, technology, engineering, and mathematics (STEM), with most evidence coming from informal and after-school spaces or elective classes. A review of research on Making in formal STEM education identified positive effects, most often in knowledge of electric circuits. Research on Maker teacher preparation, however, is limited. This 5-year study, situated in a university physics class for preservice and in-service STEM teachers and future teacher educators, explored the effects of adding a Maker component to the course. There was no statistically significant difference between the Maker and non-Maker groups on a common conceptual learning assessment. Qualitative analysis, however, provided evidence that the Maker project enabled activation of conceptual knowledge, enhanced student engagement, legitimated students' funds of knowledge, and revealed affordances of Maker learning to future teachers.

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I. INTRODUCTION

The early 21st century saw the rise of the branded “Maker” movement with the publication of *MAKE* magazine in 2005 and the introduction of Maker Faires in 2006 [1]. Making in this new context has been cast as a resurgence of making things for the personal joy of doing it—an outlet for creativity in the modern, industrialized world where Americans have lost their practice of making things at home by hand [2]. At the same time, however, it has focused on expensive, innovative digital tools and the need to drive innovation in an economic sense [3]. Some scholars have pointed out that this focus on digital production and commercialization in the new, branded version of Making excludes traditional practices of working-class communities, who have historically made things for themselves and continue to do so. Popular representations of Maker creations have also not typically included work traditionally done by women (sewing and other

needle craftwork), nor are traditional handcrafts, such as wood or ironworking, typically showcased [3].

The Maker movement quickly expanded to include programs for students and other novices in after-school and museum programs, such as the Exploratorium Tinkering Studio and MIT's Fab Lab, as educators and education researchers saw its potential for STEM learning, engagement, and identity development [4,5], and the democratization of production [6,7].

Maker education has also been advocated as a means of promoting equitable access to science, technology, engineering, and mathematics (STEM) for underrepresented groups, including students of color and students from working class communities [6], addressing gender gaps in STEM [8,9] and enabling success for students who are not typically considered to be STEM-capable and do not do well in traditional classes [10,11] and students with disabilities and autism [12,13]. However, scholars have also questioned the equitable nature of Making in elective spaces and argued that to be truly equitable, it must be more widely available, i.e., in formal school settings and curriculum [1,14,15]. Recognizing this need, the last two decades have seen a movement from after-school and extracurricular Making toward incorporation into formal education, and, more rarely, required STEM coursework. It follows other student-centered curricula (inquiry-based

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science, engineering design, and project-based instruction) with which it shares a common focus on active engagement. Maker education, however, is uniquely characterized by its focus on the student's individual creation of a personally meaningful product in interaction with an extended community, including students' home communities, online communities, and the Maker community itself [16].

Drawbacks and challenges have also been identified for Maker learning in STEM classes. Some scholars see roadblocks to effective implementation in its focus on expensive, high learning-curve digital technologies [17], its commercial nature and focus on stereotypically white, male norms [3], arguing that it “created exciting new opportunities for some, but it has arguably exacerbated educational inequalities—providing valuable resources to a privileged few while reinforcing gender and racial stereotypes” [18]. Others warn that some of the features that have made Making successful in informal settings, e.g., voluntary, self-paced participation and lack of formal assessment, could be untenable in a formal school setting with strict assessment schedules and standardized testing [19].

Making in formal settings might also require an expansion of our view of science education [9]. A comprehensive survey of peer-reviewed literature on Making in formal STEM education identified opportunities to learn beyond what is typically taught in K12 STEM classes [20]. Research specifically identifies technology literacies, including exploration (expression, tinkering, learning, and discovery) and fabrication (invention, construction, and design) skills, as critical learning outcomes of Making [21]. These findings lead to questions about whether Making in physics classes would prompt a reimagining of physics learning and a redesign of curriculum and structure for both K12 students and preservice teachers, with a goal of enabling them to *use* physics rather than simply to *know* physics. Thus, Making as an educative practice has the potential to help transform what counts as learning, who can learn, and the ways in which learning can take place, a step toward equity in education [4].

The burden of addressing the challenges of Maker education, however, will fall on teachers, the majority of whom will not have had experience with Making as learners themselves. Research on how teachers learn and learn to teach with Making is scarce [20,22]. Navigating the tension between Making and formal education will require specific attitudes and knowledge on the part of teachers. Teachers must implement Making, where the focus is on a personally relevant product rather than predetermined learning goals, in a system constrained by large numbers of specific (and sometimes arbitrary) standards that will work against playfulness and freedom to express oneself artistically that are inherent in Making [23]. They must also meet the challenges and discomfort of dealing with unfamiliar equipment and materials, wide-ranging student interests, and a lack of predetermined structure.

For more than 10 years, the Maker community has identified the need “to build a body of practice in teaching [M]aking and develop a corps of practitioners” [24], arguing that additional empirical research is needed “to develop a critical understanding of how Making is enacted in different formal educational communities, how it is lived by both students and teachers, how it shapes teaching and learning processes, and what kinds of knowledges are privileged in such environments” [25]. More recently, Blikstein and colleagues made an eloquent appeal for research into effectively incorporating Making into the formal STEM curriculum itself [15].

A survey of representatives of institutions not implementing Making as part of their teacher preparation programs found that only 7.3% did not see the Maker movement as worthy of addressing in teacher education; a much larger percentage identified lack of funding (36.7%), lack of interest from faculty (38.6%), and being unsure how/whether standards could be met in a Maker education environment (16.5%) as the reasons they did not include it [26], pointing to the need for an expanded evidence base on Maker education. Preservice teachers themselves have concerns and misconceptions about Making, again highlighting the need for additional research on Maker teacher preparation [27]. However, the Maker education community has yet to settle on a clear set of guidelines for Making in precollege education or teacher preparation. This leaves practitioners the task of incorporating Making efficiently at scale, particularly at the secondary level, without the structural changes and training on new equipment, materials, and teaching practices necessary to support all students [3,20].

The work reported here responds to these calls for research on Maker teacher education and how Making can remake formal STEM curriculum. We investigated Making over a five-year period in a college physics class designed for secondary STEM preservice and in-service teachers and future teacher educators, using the *Physics by Inquiry* curriculum [28]. The study is part of a larger effort to explore the interaction of Making and learning in teacher education.

The research questions were as follows:

- (1) What evidence is there of an impact of the Maker project on outcomes such as conceptual understanding, engagement, and persistence?
- (2) How did students' funds of knowledge from home, interest, and Maker communities interact with learning?
- (3) Did future teachers recognize affordances of Maker learning?

II. PRIOR RESEARCH

A. Research on Maker education for teachers

Research on Maker education for teachers has focused primarily on elementary teachers and teachers in informal

settings and elective courses and has largely centered on engagement and affective characteristics such as confidence. A common approach is for preservice teachers to first engage as learners and then use the artifacts and Maker projects they have designed in practice-teaching their own students. This approach allowed future teachers to gain an appreciation of student abilities [29,30] and use their funds of knowledge [31] to (a) transform making practices into personally relevant learning activities, (b) position themselves as experts, (c) facilitate mutual learning, and (d) provide a significant resource for creative ideas in advancing [Maker] projects [22]. Researchers have also focused on the effect of Makerspaces in expanding teacher understanding of the applicability of Making in education [32] and on developing frameworks for viewing and evaluating the Maker education learning experience [33,34].

B. Research on learning about electric circuits

In the area of electric circuits (the predominant physics employed in the Maker projects in our study), the research base on learning, including teacher learning, with the *Physics by Inquiry* curriculum is robust [35–37]. The curriculum was designed specifically to prepare precollege teachers to teach physical science and physics. Research on Maker education has also focused on learning in the area of electric circuits as one of the predominant areas of investigation. Student learning was documented in the area of electric circuits (and coding) in an e-textile (textiles augmented by the addition of electric circuits) workshop course in a school setting, identifying the importance of an aesthetic component in Maker projects and demonstrating the potential of e-textiles to “diversify student perspectives on who can and should participate in crafting, computing, and engineering” [38].

A review of research on Maker education in formal STEM settings identified 20 pertinent articles, all published in 2014 or later, primarily between 2017 and 2018, with learning in the area of electric circuits being by far the most commonly reported [20]. The same systemic search only yielded two quantitative studies: One showed no enhanced learning for students experiencing an electric circuits curriculum unit focusing on e-textiles compared to those who experienced a traditional circuits unit, but found enhanced positive perceptions by friends and peers among the Maker students, as well as higher reported engagement from their parents [39]. The other quantitative study found statistically significant improvements in understanding (the design) of circuits and in the ability to read code to control circuits after a unit on e-textiles in an elective high school interdisciplinary STEM class [40]. More recent work found that a large-scale intervention involving the creation of e-textiles in both informal and formal upper elementary education had a significant positive effect on students’ knowledge of electric circuits and programming. However,

the same study reported a gender gap favoring males in post scores on self-efficacy in the same two areas [41].

C. Research on Making in physics classes

Less has been reported about Making in high school and introductory college physics classes specifically. This is despite the fact that electric circuits, a common component in standard curricula, present many opportunities for Maker projects, as evidenced by the large research base on e-textiles. One case study that was reported investigated two upper-level precollege physics students in Israel taking part in a required “maker-based” engineering inquiry not associated with an organized class. Although the project undertaken by the students (design of a tracking system for a solar panel) might properly be considered an engineering design study, with design constraints negotiated with their instructor or mentor, it also aligned with Making pedagogy in that the students elected the topic based on personal interest, rather than strict alignment with a schedule or curriculum standard [23].

The study found mixed results regarding student learning, with one student taking on an engineering role, which entailed the learning of foundational physics, while the other remained in the role of a technician. The student in the role of engineer arguably developed, as well as used, knowledge of circuits and electronics. The student who adopted the role of technician (one who typically did not find a way to participate in a regular physics classroom) gained “a sense of agency and efficacy with regard to science” but “learned very little physics from [the Maker] experience.” This qualitative study also included interviews with physics educators that highlighted the need to foreground the physics inherent in the Maker project, as well as the hazards of group work in a Maker setting [23].

III. THEORETICAL FRAMING

The constructivist learning theory behind *Physics by Inquiry* holds that knowledge is actively constructed in the mind of the student, rather than simply transmitted intact from an authoritative source [42]. Constructionism, the learning theory behind Making, likewise holds that knowledge is constructed by the learner, but additionally argues that “the best way to do that is to build something tangible—something outside your head—that is also personally meaningful” [43]. Following *Physics by Inquiry*, students manipulate physical objects. One might argue that they create new artifacts in the form of electric circuits, for example, but these physical artifacts are strictly in the service of learning. In contrast, Maker learning is focused on the creation of a new physical (if possibly ephemeral) artifact that is personally meaningful, enjoyable, and unique, such as those created by students in this study [9,16]; learning happens in the service of creation.

Following the constructionist framework, we expand the traditional boundaries of physics knowledge to encompass the ability to use physics to manipulate physical objects in multidisciplinary environments to produce tangible, shareable artifacts. Researchers have argued that useful, robust knowledge is *acquired* through authentic (coherent, meaningful, and purposeful) activities and is *activated* when the need for it arises in an authentic task. Concepts acquired in “school science” can remain inert outside of that context [44]. The creation of physical objects not only provides “an evolving representation of the learner’s thinking” [45] but also facilitates learning through enactive and embodied cognition [46]. Physics understanding in the area of electric circuits, for example, can be both developed and observed as a student designs, builds, manipulates, and shares a circuit to light up a Christmas sweater or a skateboard.

This shift in perspective is not a trivial one for the academic physics community, in which abstract theory is often viewed as the target form of knowledge and is privileged over the physical work of crafting and construction that is more common in working-class communities. We see in this shift from “school physics” to “Maker physics” the possibility of enhancing the physics identity of learners and creating a bigger draw for participation STEM [9].

We are also guided by a “funds of knowledge” framework [31], which views cognition as distributed [47]. In this perspective, understanding is not just resident in the cognition of individual learners and the social interaction between them, but also in the tools, materials, customs, and processes developed by a community over time. Likewise, cognitive labor can be distributed among individuals and tools. For example, a circuit diagram is one such tool in the physics community, as is a voltmeter or Ohm’s law. Knowing which tools to use and how to use them in a given circumstance is a component of knowing physics.

The focus on community knowledge and practices has been identified as central to Making [9,16]. The Maker community has developed its own tools and generated its own environment for interaction among community members and the sharing of resources. Through commercially engineered settings such as *MAKE* magazine, Maker Faires, and Maker Ed [48], resource vendors such as Adafruit and Sparkfun, and their accompanying community-generated libraries, and organically arising resources such as GitHub, shared Maker pages on social media, blogs, etc., the Maker community enables distributed cognition. It empowers and enables learners to create things they would not have been able to make on their own.

As noted above, however, scholars have raised concerns about the white, middle-class, male focus of the Maker community, and some have worked to expand the Maker community to include working-class students and students of color [6], as well as women and girls [18]. Buechley, for example, developed the Arduino-controlled LilyPad resources specifically to address the gender imbalance in

Maker opportunities. The LilyPad tools were intended to spark the evolution of a new engineering and design community, one that enhanced access to Making in the traditionally female domains of textiles and sewing [49]. Voussoughi *et al.* assert that all communities, *particularly* the most disadvantaged, engage in Maker practices, not only making the products they need to survive, but imbuing those artifacts with personal meaning, creativity and “quotidian beauty.” In this framework, working-class communities and communities of color are seen as “sources of deep knowledge and skill” rather than disadvantaged and in need of intervention to address a deficit, as they are positioned in much of the Maker education literature, when they are considered at all [3].

For this reason, we include a much broader sense of community in our framework—one that moves beyond the recent and largely corporate-sponsored Maker community in the United States, with its focus on digital making and often-expensive tools such as 3D printers—to include the funds of knowledge and traditional tools of working-class communities (e.g., sewing, craftwork, woodwork, and metal work) [31]. Thus, we value the knowledge and strengths of the communities that have maintained these skills over time and remove the need for a digital interface between the hands (human maker) and the objects created [17]. Although Maker education is often equated with the use of digital tools, we join other scholars in recognizing the fatal flaw in equating the power of Making with its innovative digital tool set [50]. In his formulation of constructionism, Papert also warned against the dangers of “technocentrism”—an overt focus on digital technology, rather than the use to which it will be put, in education [43].

IV. METHODOLOGY

A. Setting and participants

This study took place over 5 years in a one-semester, 3 h per week physics class using the *Physics by Inquiry* curriculum [28]. The course goal was to promote deep conceptual understanding of fundamental physics, particularly as needed for K-12 teachers in our state. Two of the authors served as instructors for the course in different semesters. The course counted as an option for a required science course for nonscience majors, an elective course for physics teaching majors, and an option for a required science course for nonphysics STEM teaching majors and STEM Education graduate students. The participants ($N = 88$) were about half preservice teachers, with the rest equally divided between STEM Education graduate students (former and current teachers) and other students for whom the course fulfilled a general science requirement.

In the course as originally designed, students worked in groups to complete the Electric Circuits and Light and Optics sections of *Physics by Inquiry Volume II*, [28] following the University of Washington lesson and exam

format closely. These two curriculum topics were selected to align with state high school physics standards, focusing on topics not necessarily emphasized (or even taught) in the standard required physics courses for future teachers at our institution. One course instructor (first author) had been trained at the University of Washington summer workshop for teachers. Beginning in 2015, the syllabus offered a Maker project option, which would count toward the final course grade, lowering the percentage that counted toward the final exam.

Beginning in 2016, the course was designated a science core course for undergraduates, and a Maker Project became a regular, scheduled part of the curriculum. By including “educative Making” [9], we aimed to provide a learning environment that focused on process and iteration, personally meaningful activity, community interaction, and broader ideas of what it means to learn and do physics and who can achieve those goals.

The Maker project assignment was presented at the beginning of the semester, and students were given examples of Maker projects. Later in the semester, students completed an in-class project in which they created a picture that would light up using LEDs and copper tape as an introduction to LEDs, an example of “creative construction” [9]. Students then completed an additional maker project of their own choosing, with the project counting for 15%–20% of the course grade. Students who did not wish to complete the extended Maker project had the option of continued independent study of the course topics and having the final exam count for a larger percentage of the course credit. Prior to the 2020 pandemic, all students elected to do the additional Maker project. In 2020, the shortened semester was hybrid, combining in-person and online instruction, and the syllabus was altered to cover less of the optics portion of the course. That semester, 4 students who were participating completely remotely (out of 20) opted for further study of optics and electric circuits in place of the Maker project.

Projects were evaluated on four aspects according to a rubric: originality/personalization, persistence/revision, documentation, and technical challenge/accomplishment. Students were required to document multiple iterations of project design and to describe challenges they faced and how these were surmounted. Students were not judged on the appearance of their projects, although they were encouraged to think about how they might “clean up” these projects (e.g., secure batteries and wiring) and anticipate future use to make them more robust in future iterations [51]. This, combined with the focus on creativity and originality, worked against typical classroom norms that discourage students from taking risks and trying to learn beyond what is required [7].

Students in the course were required to document and submit their work each class day. They were also required to present their design process at several designated sharing

sessions with peers and to submit status updates at three points prior to submission of final documentation, providing opportunities for feedback and self-assessment. They were encouraged to document the project with photographs and videos at all stages, particularly in the case of successes, but also in the case of failures, prompting them to reflect on their Making process [52].

Almost all of these projects were classified as “tinkering,” although three students engaged in “assembly Making” and built something directly from a kit: a flashlight, a telescope, and a 3D printer (which was then used to make other things) [9]. To accommodate the two class sessions spent on Making and sharing Maker projects, the concave lens section from *Physics by Inquiry* that was sometimes included was made optional, and the review for the final exam was moved outside of class time. Thus, the Maker project primarily augmented rather than replaced the curriculum. Although students in all but one case (a team of two) undertook an individual Maker project, in all cases, students collaborated with a broader community, at the class level and beyond, for feedback, brainstorming, and resources.

B. Data collection and analysis

The study followed an approved Human Subjects Research protocol and comprised both a qualitative and a quantitative component. The quantitative analysis was designed to determine the effect of adding the Maker component to the curriculum on standard measures of physics concept learning. It consisted of a statistical analysis of final exam scores both before and after the Maker project was added to the course.

The qualitative analysis provided a much richer view of what it meant to learn and teach physics in a Maker environment. For the qualitative component, instructor notes, student project status submissions, video recordings of project presentations, discussion posts, emails and final project documentation were collected and reviewed by the three authors. In a preliminary round on a partial dataset (the first two years), the authors independently engaged in open coding, reviewing artifacts to identify concepts that arose in the data and to develop a coding scheme through analytical memos [53]. In a second round, individual coding was compared to develop a revised list of concepts and coding scheme and group concepts (subcodes) into preliminary categories (codes). Three iterative rounds of coding were then implemented on the complete dataset, and any disagreements in coding were negotiated until a final resolution was reached.

V. RESULTS

Results as applied to the research questions are described below. Final qualitative codes used to address each question, along with descriptive subcodes, are listed in the corresponding sections.

A. Impact of the maker project on conceptual understanding, engagement, and persistence

Existing research at the time the Maker component was introduced into the course hinted at possible positive effects, but there was also a documented concern among preservice teachers that devoting time to the Maker project would have adverse effects in the classroom [27]. This is certainly a concern not only in the context of standardized testing but also in the case of the assessments developed for *Physics by Inquiry*. This curriculum was carefully designed, through painstaking research, to address difficulties students encounter in conceptual learning of specific content, in this case, electric circuits and geometric optics [36]. The concern was greatest in the area of optics, as only 3 of the 87 projects dealt with optics. Further, although the remaining 84 projects all dealt with critical conceptual understanding of electric circuits, not every project provided evidence of all the concepts covered in the course. This points toward a possible mechanism to decrease electric circuits learning as well due to decreased time engaging with the research-based curriculum.

Of course, an effect on conceptual learning (positive or negative) is not the only possible effect. Following our constructionist framework, we also considered the ability to activate conceptual knowledge, e.g., apply it in an authentic context. Affective outcomes, both positive (engagement and persistence) and negative (frustration), were also investigated, as well as perceived success or failure.

1. Conceptual understanding

Results of a statistical analysis of exam scores and qualitative coding, specifically the codes shown in Table I, were used to investigate the effect of the Maker component on conceptual understanding.

For the statistical analysis, we took advantage of a “natural” experiment, comparing scores on final exams for 4 years prior to the inclusion of the Maker project ($N = 52$) and three years afterward ($N = 52$). During this time, an essentially identical final exam was administered to the class. In all sections, students completed a pretest prior to the beginning of instruction.

TABLE I. Codes relating to conceptual understanding and its activation.

Subcodes	
Physics	Resistance, voltage (ground), current, series, parallel, short circuit, open circuit, insulator, conductor, circuit diagram, Ohm’s law, reflection, refraction, projection
Construction	Troubleshooting, batteries, LEDs, capacitors, transistors, conducting tape, insulated wire, soldering, wire wrapping, controllers, sound modules, suppliers

This pretest includes two questions. In the first question, students are asked to rank bulbs by brightness in three circuits: A single bulb, two bulbs in series, and two bulbs, all in parallel with an ideal battery, assuming identical bulbs (see Fig. 3 in Ref. [35]). In the second question, these three circuits are combined as three branches in parallel with one battery (see Fig. 2 in Ref. [35]). Pretests are scored either as complete (a correct answer to all sections of the problem with accompanying correct reasoning) or incomplete (not meeting requirements for a complete score). Students with a prior physics class will often rank each of the bulbs in the parallel circuit in the first question brighter than the single bulb, based on a misapplication of the algorithm for total resistance of parallel networks (individual bulbs are brighter because “total resistance is much less in this case”). Students without prior experience will typically rank bulbs in parallel as being dimmer than the single bulb because they “split” the current from the battery (“bulbs in parallel split the brightness from [the single bulb]”). Likewise, the bulbs in series are sometimes ranked as being dimmer than the single bulb because they split the current from the battery, each taking half, or that the bulb nearer to either the positive or negative side is brighter (“2a is brighter than 3a because it has a power draw on its negative/ground side”). These responses all indicate an incomplete conceptual model. It is extremely rare for students in the class we studied to provide a completely correct answer to both questions with correct reasoning; there was never more than one student in a class whose pretest scored as complete; in the entire Maker sample used for the statistical analysis no student did, and in the non-Maker sample only 1 student did.

There was no significant difference between the Maker and non-Maker sections on the *Physics by Inquiry* electric circuits pretest scores. We therefore used a t test to compare Maker and non-Maker performance on the final exam, which was administered close to the completion of the Maker project.

The exam contained problems modeled on those in the *Physics by Inquiry* curriculum. Students ranked the brightness of bulbs (a proxy for the current through them) in complex circuits and described how the ranking would change when specific changes were made to the circuits. They analyzed electrical circuits, identifying series, parallel, and combined networks and calculated currents through and voltages across individual resistors and networks of resistors. They created ray diagrams illustrating the formation of images with masks (including pinholes), mirrors, and lenses. They were presented with examples of student thinking and asked to evaluate it, and how they would help these students improve their reasoning as needed. They were required to explain their reasoning; using a memorized algorithm without an explanation was not sufficient.

Although the average score for the Maker students (89.9 with a standard deviation of 8.6) was slightly higher than

for the non-Maker (87.3 with a standard deviation of 13.9), there was no statistically significant difference between the two groups ($t = 1.33$, d.o.f. = 84.98, $p = 0.26$). Thus, the addition of the Maker project neither enhanced nor detracted from students' acquisition of conceptual knowledge and skills typical with the *Physics by Inquiry* curriculum, as measured by a typical assessment instrument.

Our qualitative coding also provided evidence of conceptual learning. Every project in the study was coded as demonstrating learning of at least one physics concept relevant to the curriculum (Table I), and collectively, the projects involving electric circuits addressed all of the relevant concepts repeatedly. Students were exposed to the concepts used in other students' projects through regular sharing sessions, informal classroom discussions, and the class discussion board.

Our coding did identify places where students in our study (six cases) used a term incorrectly or made an error in a diagram in their Maker reflections. For example, one student (a second language learner) spoke of "a resistance of 2.5 V" and two others, one a second language learner, referred to LEDs being in series, when in fact they were in parallel. In all three cases, students had constructed a working circuit with an accurate diagram. Rather than seeing this as a flaw in conceptual understanding, we saw this as either a case of misspeaking, or, where knowing the right vocabulary, although important, was not necessary to understanding the physics of the circuit [54]. Another student drew the electrical connections to the bulb symbol in his circuit diagram incorrectly (connecting to the glass rather than to one end of the filament). This indicates that the concept of representations of electrical connections in circuit diagrams, carefully addressed in *Physics by Inquiry*, was not completely developed for this student, even after completion of the Maker project.

In our qualitative assessment, however, we also identified many instances where students showed evidence that interacting with the Maker project, and the struggle it entailed, enabled *activation* of prior conceptual knowledge beyond what had been achieved by the research-based *Physics by Inquiry* curriculum, noted for its ability to enhance students' conceptual learning [35–37].

In one example, a student with experience in digital electronics struggled to get a microcontroller to command a programmed sequence of blinking LEDs in his "bottled lights" project. He wanted to make a jar of randomly blinking lights like "lightning bugs in a jar," which he had loved as child [Fig. 1(a)]. After days of testing, rebooting, replacing microcontrollers and power supplies, and searching the Internet for suggestions from the community, he finally stumbled on a post from another user indicating that what had fixed a similar problem was to make sure that the microcontroller was actually tied to the same "ground" as the LED strip, thus completing the circuit. Doing so fixed his problem. This was, in his words, "in hindsight a bit

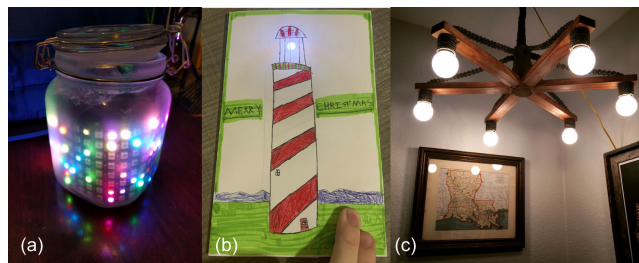


FIG. 1. Examples of Maker projects: (a) "bottled lights," showing a struggle to apply previous conceptual knowledge, (b) "light house card," made for an uncle, and (c) "ceiling light," showing an object made for student use.

amusing given it is literally the first lesson we have in what a complete circuit design requires."

Indeed, the very first exploration in the Electric Circuits section is to light a small, incandescent bulb with a D-cell battery and one wire, requiring students to complete a circuit. Although all groups were (eventually) successful in this task, and students rarely had difficulty employing the concept to analyze circuit diagrams and complete tasks with physical circuit elements by the end of the unit, there was still a leap when transferring the knowledge to a less archetypal circuit.

One student (see "Persistence" section below) calculated that she needed a 50- Ω resistor for her circuit, but only 200- Ω resistors were available. She tried to construct her own resistor from nichrome wire, but it took meters and was impractical. She was stumped until the instructor asked how she had responded to a *Physics by Inquiry* question about how to make a 5- Ω resistor out of 10- Ω resistors. Although she had previously responded correctly, the knowledge was not automatically activated.

Another student making a present for his partner was trying to get the LEDs he was using to light up more brightly. For help, he posted a question about what others had tried to a class discussion board. Another student responded that she had tried wiring the LEDs in series, where they were too dim, but then had success making them brighter with a parallel configuration. He later described his response to her in a class discussion as, "That's *brilliant!* Of *course* they would be brighter in parallel!" Despite the heavy emphasis on identification and interpretation of series and parallel networks in the *Physics by Inquiry* curriculum, and students' successful interpretation of circuit diagrams and construction of the corresponding circuits, this knowledge was not immediately activated for these students and for many of their colleagues when they needed it to design a circuit. Students without electrical design experience frequently defaulted to a series configuration in their designs.

Activation of conceptual learning in context also requires knowledge of the tools, components, and methods of construction appropriate in that context. Although students

had not worked with LEDs in the *Physics by Inquiry* curriculum, their creations often called for them, for example, in the case of cards, calendars, and other applications that need “flat” bulbs. To take advantage of LED technology, students had to adapt their well-developed conceptual model of the functioning of resistors in electric circuits. One student noted that she had to “adjust my model of electric circuits slightly because I was using LED bulbs, which require more thought in the placement of the parts of the circuit since the current flows in a specific direction and the components need to be attached correctly.” Students also had to expand their understanding of switches, as the knife switches used in *Physics by Inquiry* were not appropriate for most of their designs. One student recorded that “[t]he switches work in the same way, because they are either meant to stop or start the flow of current, which is exactly what happens with switches with wire and with tape. I just found making the switches is a little more complicated [than] that when I first started this project.” Several created their own novel means of switching current in a way “without a physical switch in the circuit” and one whose operation was readily apparent and easy for anyone.

2. Personal engagement

Our qualitative coding also identified affective outcomes associated with adding the Maker project. The first of these was personal engagement (Table II). Given that students selected what they would make, and in most instances devoted considerable time, well beyond what was required, to the project, it is not surprising that the large majority of projects were coded as personally meaningful. Students very often explicitly reported (80%) that they were working on something important to them as it was something they needed or wanted, often to give as a gift. One student made a Christmas card for his uncle, who “loves helping manage the lighthouse for his small town,” showing the lighthouse with a functioning light [Fig. 1(b)]. Another student who shared a house with roommates felt they needed more light. He created a ceiling light modeled after the artificial moonlight towers in the town where he lived, which had fascinated him [Fig. 1(c)]. Many students noted in their reflections that the project was of great value to them in terms of what they learned or were able to show that they could do. Students expressed

TABLE II. Codes relating to personal engagement.

Subcodes	
Personal meaning	Indicated use or recipient, personal value, pride, connection to an interest, issue, religious or cultural practice
Enjoyment	Fun, enjoyment, engaging in an activity they loved, providing a break from “schoolwork”

pleasure and pride in their projects, particularly after overcoming problems and setbacks. About half of our students (52%) explicitly expressed in their reflections the joy and excitement of finally getting something to work, e.g., having “literally screamed very loudly with joy at [a] small but monumental advance.” Yet another stated, “I’ll put it in my room and just like remind myself of a cool project I did and I’m pretty proud of it.” While a few had previous experience with Making in some form, many created an authentic, working circuit (or, less often, optical system) for the first time, sometimes saying that they deliberately wanted to try something new, and the Maker project presented an opportunity. A student who learned to sew in order to make a light-up Christmas sweater sent a video of himself dancing when he got a circuit to light, with the annotation “**IT’S FINALLY LIGHTING UP.**” Field notes and emails, from well outside of class hours, documented delighted “Aha” moments and reports of wearing and sharing what they had made.

3. Persistence, frustration and failure

Another group of codes, addressing qualitative outcomes related to persistence, is given in Table III. Our frequent coding of “persistence” was also an indicator of engagement; we also, however, coded examples of frustration and failure. The large majority of projects (89%) explicitly documented at least one problem encountered that required a substantial revision before reaching a working prototype. Only two were completed within the allotted class work sessions and met only minimal requirements to receive partial credit, arguably indicating a lack of engagement. Many gave multiple examples of problems and having worked (sometimes for days) to figure out a solution. One made a table cataloguing 12 difficulties she encountered and how she overcame them. Figure 2 shows the first 4. Despite documenting (often numerous) iterations toward the final product, only nine students explicitly documented frustration, occasionally obliquely, as in the case of a student who had struggled with soldering (at possible risk to her deposit when the iron fell on the floor in her rented apartment) but finally was successful simply twisting wires together and wrapping them in electrical tape. Upon hearing that another student had been successful with a wire-wrapping tool, producing a connection that is typically more robust in terms of thermal shock, she announced

TABLE III. Codes relating to persistence.

Subcodes	
Persistence	Extended time, iteration, improvements, modified solution
Frustration and failure	Indications of frustration, failure to bring a design to completion

Original Plan	Problem that Arose	Solution and Improvement
Flat LEDs to light the mushrooms	It was near impossible to find any flat LEDs, only rounded ones like this were available. However, they require less current so they are dimmer.	I used the rounded LEDs since that was what was available. I changed my calculations to accommodate this, so I needed to find a 50 Ohm resistor. To make these new LEDs appear brighter, I cut the top acrylic dome off (still protecting the light).
I now needed a 50 Ohm resistor, instead of a 100 Ohm resistor (required for flat LEDs).	The only resistors available in great excess during the maker project session were 200 Ohm resistors.	I tried to make my own 50 ohm resistor using nichrome wire and measuring the resistor with a meter. This took <u>meters</u> of wire.
My new and improved* plan was to make my own 50 Ohm resistor with nichrome wire.	I had to wrap the wire around itself so many times to fit along the wire stem I had created. When I re-tested the wire that previously read 50 Ohms on the ohmmeter, it read 5 Ohms because it was so wrapped around itself it couldn't create the same resistance it had stretched out.	I had given up on making my own resistor, so I was just going to order some on amazon.
My new and improved version of my "new and improved plan" was to just order a 50 ohm resistor on Amazon.	Even though I have prime (free 2 day shipping), due to the holiday week, no one was shipping goods until that Friday or Monday.	I created a customized 50 Ohm resistor by just placing 4 200 Ohm resistors in parallel with one another, and soldering these in series with the LED light.

FIG. 2. Student design document table listing original plans, problems that arose, solutions, and improvements.

to the class, "I wish had known about that before!" Of the nine students, three paired their reported frustration with indications that the effort was worthwhile, e.g., "The eureka moment of the seeing the pinwheel light while spinning was also extremely rewarding, as it was a long and painstaking process to get it to that point," "I didn't realize how much trouble I was going to have; I felt pressed for time; decided to go back to original design; immensely more difficult and tedious but immensely more rewarding," and "There were a lot of obstacles that had to be overcome such as finding the right drivers and code in order to get the Arduino and circuit boards to respond, however, the experience of working on this project was so valuable in

that I learned how to do something that I had never done before."

In no case was a student unable to create a working prototype for their project. However, in nine cases, students did document a major revision or a complete change to their projects. In most cases, this was due to obstacles encountered with the original project, most often difficulties in obtaining supplies or an inability to see how the project would be implemented. In three cases, however, it was because students identified a different project that excited them more, as in the case of the student who noted, "I am glad that I changed my idea because the outcome was something that I was more passionate about and I learned new things."

There were also six cases in which projects that worked at one point eventually failed on repeated use or in an attempt at improvement. This was primarily attributable to electrical connections that were not robust enough to withstand repeated mechanical or thermal stress. This was the case, for example, with a “Steampunk” hat augmented with moving gears with micro-LEDs that was accidentally dropped in a puddle while being transported to the class.

B. How do students’ funds of knowledge interact with learning?

Qualitative data were used to address this question; codes related to community funds of knowledge are listed in Table IV.

Perhaps not surprisingly, we found numerous examples of engagement with the Maker community enabling distributed cognition. A small number of students worked with iconic digital manufacturing tools of the Maker community available either at home or in campus Makerspaces (e.g., 3D printers and laser cutters), with success in some cases, but considerable frustration in others. Two of the four students using 3D printers reported substantial struggle that possibly outweighed the benefits. One reported that “The most difficult part of my project was the 3D printing portion.” It took 5 h for her electric heart model to print despite the fact that she had spent longer than that optimizing the code.

Another student using a printer to make a frame for a wall-mounted Raspberry Pi computer found that “the 3D printing ended up shrinking some of the measurements.” She “ended up having to melt part of the frame so that the side panels would fit as well as the back panel. The front panel was not able to be screwed onto the frame since the frame was tampered with, so it had to be taped onto the rest of the body with heavy-duty double-sided tape.”

The promise of 3D printing to provide opportunities for rapid prototyping and “professional” products [7] did not materialize, at least not for all students. The intermediary between the hands and creation of a product changed from manual dexterity to coding skills and access time on the printer [17].

TABLE IV. Codes relating to community funds of knowledge.

	Subcodes
Community engagement	Maker community, classroom community, online communities, friends and family, interest groups
Maker tools	3D printer, laser cutter, digital carving machine, LilyPad, Chibitronics, controllers
Tools	Traditional women’s tools, traditional construction tools, soldering, computer tools
Aesthetics	Artist and decorative craft communities

One student for whom 3D printing was entirely successful said that he had been “tinkering with all sorts of things since [he] was a little kid” and always found technology fascinating. A reader of *MAKE Magazine*, he was the only student in our study who self-identified with the branded Maker movement prior to taking the class. He had taught himself to solder, played with Arduino and Autocad, and, with the proceeds from a “small business” he had fixing phones for teachers and other students in high school, bought a discounted 3D printer off the Internet.

This student had not seemed particularly engaged with the *Physics by Inquiry* assignments; he had, in fact, declined to submit assigned essays other than the reflections on the Maker project. The Maker project, however, clearly gave him a chance to showcase his funds of knowledge. He first planned to build a model car and his supplies request included two small dc geared motors from Sparkfun. After a wiring mistake caused one of the motors to burn out, he ultimately converted his project to a model boat, using his mother’s hot glue to insulate the electric components. He shared a video of his boat using the online Wondershare FilmoraGo tool. His project received the most positive comments from classmates. In an email, he expressed that he was honored to have his work recognized.

Other students using more advanced computing tools associated with the Maker movement (Raspberry Pi, Arduino Nano, Arduino Metro Mini) experienced problems, for example, compatibility issues and problems loading data files and drivers. In contrast, microcontrollers specially designed for the intersection of Making and sewing and/or decorative crafting presented a much lower entry barrier to Making. The LilyPad Arduino and the Adafruit Trinket supported handwork such as sewing and embroidery, traditionally done by women, with custom parts, instructions, and sample code. Students with experience in these areas, rarely of value in a physics class, were positioned as experts. In one case, several female students with sewing experience employed their funds of knowledge in this area to coach a male student through the problem he was having tying knots in conducting thread.

Nondigital Maker tools, for example, “soft circuits,” with conducting thread or stick-on copper tape and LEDs customized for the Maker community (e.g., Chibitronics) also enabled first-time crafters to successfully incorporate electric circuits into textile craftwork [Fig. 3(a)] as well as

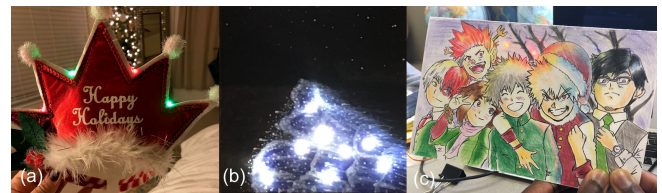


FIG. 3. Projects using nondigital Maker tools: (a) holiday crown, (b) bioluminescence painting, and (c) anime card.

decorative greeting cards and wall art. These Maker tools enabled students to showcase and share their artistic talent and add aesthetic value to their products. One student was able to combine her “newfound interest in physics and understanding of electric circuits with my personal goal to nurture [her painting] hobby.” She represented bioluminescence, a biological phenomenon that had always fascinated her as a science teacher, using electric lighting [Fig. 3(b)]. Another student, who loved anime and had always wanted to make his own Christmas cards, created a card based on his favorite show, *My Hero Academia*, impressing his colleagues with his drawing talent [Fig. 3(c)]. Integrating aesthetic components into Maker activities has been suggested as a way to broaden their appeal [38,55].

Students in this study also employed funds of knowledge from home and interest communities. These communities provided expertise not typically applicable to homework assignments, nor seen as valuable in physics. Students got help with analog electronics, soldering, nondigital machining, drilling, sawing, and sewing from friends, parents, and grandparents, in addition to help from instructors and classmates. This enabled some students to involve friends, family members, and personal interests in their physics coursework, often for the first time.

In one example, a student earning a secondary science teaching certificate, who had done practice teaching in a physics class, worked on his project with his parents, whom he described as “engineers.” His mother, who did not speak English at home, helped him design an analog circuit and provided him with parts (capacitors and transistors) and a soldering iron to adorn a stocking cap with blinking LEDs. Analog circuits are not as celebrated in the Maker community, but they are common, for example, in household wiring and other home applications. He was able to share the knowledge that he developed about capacitors and transistors, circuit elements not covered in *Physics by Inquiry*, with the rest of the class, positioning himself as an expert. As he described it,

Building this beanie provided a wonderful opportunity to learn about transistors and capacitors through inquiry. As far as I understand it, transistors are simply junctions that constrict the flow of current through one of two paths depending on the resistance of the path. Capacitors are devices that store charge. They can receive a certain amount of current before they become completely charged at which point they can no longer accept current. Using the ability of the capacitors to draw charge for a certain amount of time, and the transistors’ ability to redirect the flow of current, I was able to create completely analog driven sequences of blinking LEDs.

In addition to community tools and construction expertise, community traditions also served as a guiding

inspiration. Many students’ projects were centered on Christmas traditions, but a number focused on Chanukkah and other traditions. One student said that she was glad to be able to make a light-up Chanukkah sweater, because “they don’t really sell light-up Chanukkah sweaters” and another, a current teacher, made an electric menorah to share the tradition with her students. A student of Chinese heritage created a beautiful image of floating lanterns, honoring a cultural observance celebrating the last day of the Chinese New Year.

C. Did future teachers and others recognize affordances of Maker learning?

Given the expectation that teachers will teach as they were taught, at least as a starting point, we looked for opportunities for teachers to experience learning in ways not typical in physics classes. This is particularly important in the case of Maker education, where preservice and novice teachers have been found to hold misconceptions about costs and benefits [27]. Qualitative codes associated with cognition, earning, and teaching are listed in Table V.

Some of the future teachers explicitly recognized the value of learning through Making, saying, for example, “I believe the maker project helped me learn physics, in a less controlled and more exploratory way. I was motivated by this method and I learned a great deal, including significant detail for selected areas.”

1. Enactive and embodied learning

Following our constructionist framework, we looked for opportunities for learning through enactive and embodied cognition as students actively engaged in building something tangible. Some students explicitly expressed an appreciation of enactive learning in their reflections, saying “It was nice just working with my hands and problem solving as I went” and “I would figure out a way to create this switch when I had the circuit in front of me in real life.” One student noted that he could not really understand a complicated circuit until he had recreated it, drawing it out for himself.

Another example of enactive cognition was recorded in the case of a student who reported that some of the LEDs on the Christmas sweater she was making [Fig. 4(a)] were not working, possibly defective. When asked whether she had checked that her LEDs were sewn to the battery terminals

TABLE V. Codes relating to cognition, learning, and teaching.

Subcodes	
Cognition	Distributed cognition, enactive and embodied cognition
Learning	Learning from failure, constructionism
Teaching	Plans for teaching a Maker project, using their Maker project in the classroom

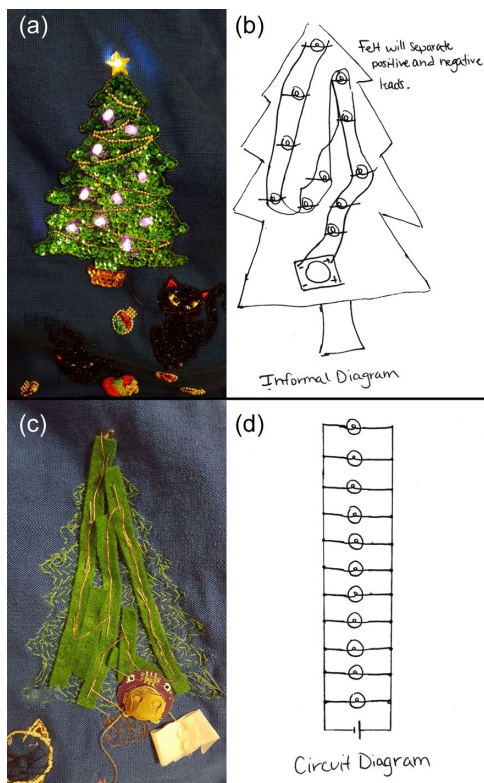


FIG. 4. Design documents: (a) result, (b) layout diagram, (c) insulation solution, and (d) circuit diagram.

(with conducting thread) in the proper orientation, she responded that “the positive leads are all on this side.”

As noted in the “informal diagram” [Fig. 4(b)], the conductors that appear to touch are actually insulated from each other [Fig. 4(c)]. She began to trace the thread from the positive side of the battery with a finger, saying, “But if they are reversed, then ...” She stopped and quickly reversed the connections to the battery to see the bulbs that had been lit go out and the others light up. She wrote in her reflection:

I knew I wanted all the lights to be connected in parallel across the battery. This is so that the lights could be as bright as they were allowed to be with the battery by reducing the resistance. In order to connect the LED lights in parallel, I poked one terminal through some felt so that I had the negative terminal of the LED lights on one side of the felt and the positive terminal on the other side. The felt acts as an insulator so that the conducting thread used to connect the lights does not have the negative and positive terminals touch. This is important so that all of the lights can turn on. When making the circuit, I encountered a problem where only 7 out of the 10 lights would turn on and I later figured out that the three lights that would not turn on were connected the

wrong way where the positive leads were on the negative side. I was able to determine this by flipping the connections on the battery because the three lights that were initially not working were the only ones that were on in this trial. This was an easy fix as all I had to do was flip the LED lights to have the right terminal on top of the felt.

This episode shows that this student (importantly) understands (i) that she wants the LEDs to be in parallel [Fig. 4(d)] so that they will all have the voltage difference needed to drive them (i.e., the entire battery voltage), (ii) that having the + and – leads touch each other will lead to a short and that she can solve that problem with felt insulation [Fig. 4(c)], and (iii) that the LEDs are polar and the + and – leads need to be attached to the corresponding battery terminals. However, when 3 of the 10 (actually 4 of the 11) lights will not light, she is stumped. It is not until she begins to trace the connections with her finger that the necessary knowledge is activated and a way to troubleshoot the problem presents itself.

2. Learning from failure

Learning through failure, not typically celebrated in school science, but considered an affordance in Making [9,16], was another common theme in our qualitative coding, for example “[I] failed a lot (but there is knowledge in failure, because now I know many things not to do).” Another student noted that, in attempting to troubleshoot a problem, she “tried testing each [LED] individually, to see which ones were functional, and burned out the battery and/or bulbs by doing so. I’m not sure which burned out, but I couldn’t get anything to work after that” and from that experience, she learned “to always be conscious of the amount of voltage being used and the size of resistors to maintain safety and functionality.”

3. Recognizing affordances of Making

In our sample, 10 of the 44 secondary STEM teacher candidates and 2 of the 4 in-service master’s students explicitly described how the Maker project had informed their teaching plans. One noted that, “As a teacher, I imagine it would be fun to see the creativity your students find in the broad topic of “optics or circuits.” Even though simulations and wire/bulb/battery kits are helpful, there is something very powerful about making something yourself.” Another reported that she “learned a ton about the inquiry process that I will apply in the future [as a teacher]” and “This maker project has really showed me how STEM can be combined with a variety of creative media to further enhance the learning experience. I hope to continue to expand my knowledge on maker projects and implement them into my lesson plans in the future.” A number of students created objects that they would use in their classrooms: a 3D printed model of a human heart showing

electrical conduction pathways, a Jeopardy style buzzer set for use in review games, a magnetic stirrer, an electric circuits curriculum module using Snap Circuits, a scrapbook to be used as a classroom reference on circuits and optics, and a homemade classroom projector. We have only very limited anecdotal information about whether and how the preservice and practicing teachers in this study went on to implement Making in their own classrooms. However, at a minimum, the large majority reported a successful experience in learning themselves, arguably increasing the chances that they might consider Making as an option in their future classes.

VI. DISCUSSION

As noted above, two theoretical frameworks informed our analysis of the results: constructionism and funds of knowledge.

A. Constructionist learning

Implicit in our theoretical framing is the expectation that students will learn physics through constructionist inquiry, that is, by constructing a physical object of personal relevance. Collectively our results illustrate how creating tangible physical artifacts can not only serve as an assessment of student thinking but also help to activate inert conceptual knowledge and build personal engagement with physics learning.

Our study revealed many instances where students were not immediately able to employ conceptual knowledge for a purpose of their own choosing outside of the familiar *Physics by Inquiry* context without engaging in the construction process (and the frustration and failure it sometimes entailed.) Our comparison of final exam results indicates that they knew how to evaluate circuit designs in the context of the standard experiments and exercises (at least as well as students prior to the introduction of the Maker project), but that knowledge did not immediately translate into being able to design a circuit for their own purposes. It remained inert. This difference between knowing a concept and knowing how to use it in a situated context has been identified by scholars who argue that approaches to learning that make use of an authentic physical and social context are required to produce usable, robust knowledge that will be activated when needed. Students may be competent at “school physics” and still be unable to use physics to accomplish something of importance to them [44].

Further, the things students made were reported to be personally meaningful for over 80% of the projects. More than half of the students who engaged in Maker projects explicitly reported that they found joy and value in the process.

It is true that some of the students produced a greeting card, not far from the example project done during class

time. However, we did not see this as “keychain syndrome,” a phenomenon identified by Paulo Blikstein, when his students were introduced to Making with a short, semi-structured digital fabrication project to fabricate a keychain. Rather than enabling students to go on to make something that they actually wanted, the scripted project only prompted students to make more keychains—even if only to sell them—because they knew how to produce them easily [7]. In our study, in no case was the final product anything like the LED-enhanced picture produced during the in-class sample project. Students who did make cards found ways to customize them and make them more aesthetically pleasing, like professionally produced greeting cards, by finding ways to hide circuitry and implement switches.

Of greater concern was the frustration and failure encountered in the course of the Maker projects, despite the fact that some students indicated that the immense difficulty made the project immensely rewarding. Further, there were cases (but only 2) where students only met the minimum requirements to receive partial credit for the Maker assignment.

Countering this concern, anonymous course evaluations did not include a single comment indicating that the Maker project was not of value. Further, despite the fact that other options were provided, only 4 students ever availed themselves of the alternatives, and that was during the semester when the course meeting time was curtailed and many students were strictly remote. Still, it is possible that the Maker project might not have provided all students with a positive experience, particularly one that carried forward to influence future teaching.

Finally, some preservice and in-service teachers explicitly recognized the affordances of constructionist Making for their own teaching, beyond experiencing its effect on their own engagement and learning. One middle school mathematics and science teacher wrote in a subsequent class, “I find [the] arguments [for Maker education] compelling because the act of applying their knowledge to something [students] create will help the knowledge be retained. I know this is true for me because of our physics by inquiry class.” As noted above, a future science teacher indicated that she imagined using such a project in her own classroom because “Even though simulations and wire/bulb/battery kits are helpful, there is something very powerful about making something yourself.”

B. Community interaction and funds of knowledge

Only one of our participants, a long-time reader of *MAKE* magazine with his own discounted 3D printer, self-identified as a member of the branded Maker community prior to the start of the class. Only six students made use of prototypical Makerspace digital manufacturing tools (3D printers, laser cutter, and digital carving machine), and only three made use of microcomputers (Raspberry Pi) in their

projects. Paralleling results of previous research on the use of advanced digital tools in Making [25], two of the future teachers who chose to use a 3D printer struggled to print something that could have been made more quickly, and possibly more successfully, by hand. Still, the experience with printing acquainted them, and others in the classroom community, with the possibilities for increased agency in the construction process and informed the experiences that they might design for future students, providing more equitable access to advanced digital technology.

The majority of the projects in our study were enabled by more easily accessible tools customized for the sewing and crafting communities or with the traditional hand crafts of working-class communities (nondigital machine sewing, hand sewing and other textile work, sawing, drilling, soldering, analog electrical wiring, etc.) allowing the students in our study to interact with communities with which they already identified. Thus, they were able to use their own knowledge and skills, as well as community resources, to their advantage.

Students in our sample relied on the resources of fellow students, friends, and family, and found a way to involve them in physics coursework, sometimes for the first time. One student wrote that she looked forward to working with her dad on the soldering for her project; she included a picture of her smiling father in her final report. The student whose parents helped him with the analog engineering for the blinking lights on his stocking cap said that it was “so cool” to get to work with his parents and see what they did. Over the course of the Maker project, parents have helped with machining, grandmothers have helped with sewing, and friends have provided Dremel and table saws, as well as a chainsaw. Students often received tutoring from colleagues in the classroom; students got help with programming, soldering, and learning to create knot to secure a thread by leaving the thread through the needle. The helpers were recognized as experts for the project.

Of course, it is important not to make possibly stereotyped assumptions about students’ interests, motivations, and skills. Not all students from working-class communities have knowledge of traditional construction tools or a family member who does. Not all students of African heritage are interested in African art. The student who created the card in Fig. 3(c) is of African descent, but he affiliates strongly with the Asian anime community, and its culture and practices supported his creative efforts. Nor do all female students have an interest or experience in sewing, particularly with increased prices (compared to mass-produced clothing) and lower access to fabric and other sewing resources. Two girls in one study almost gave up their project to make a jacket, responding to needs for fashion, warmth, and safety faced by members of their community, because neither they nor their family members knew how to sew [6]. They were able to get help from the

Makerspace where the study took place, but such resources are not available in all communities.

This heightens the need for future teachers to experience free-choice Making and develop Maker expertise, including knowledge of resources, if they are to successfully design Maker learning experiences, especially for students from communities underserved and underresourced in physics education. As seen our study, a Maker project can welcome students with a broad range of prior experiences and knowledge, allow them to create something of personal importance, support them in the process through community and classroom interactions, and position them as experts themselves. Such activities have the potential to inform students’ and teachers’ ideas of what it means to know and do physics [9].

VII. CONCLUSIONS

Our results address concerns within the teacher and teacher education communities that it is not possible to incorporate Making into a standard, required physics class without sacrificing existing learning objectives. On one hand, there is a concern that incorporating Making will limit the possibility of “covering” required standards and, on the other, that the challenges of implementing Making in a required science classroom will limit its free-choice, creative nature. Rather than being supported in the struggle to repair or create something new, students might feel constrained to replicate a demonstrated, prescribed construction process [7,56]. Formal schooling might be inherently incompatible with the essence of Making [4].

None of these outcomes materialized in our study. Students achieved at the same levels on research-based assessments of conceptual learning after the Maker component was added to the course. The Maker project, however, increased students’ ability to activate this knowledge in the service of achieving a personally relevant goal. In agreement with other researchers, we found that the process of applying concepts such as open and closed circuits and short circuits, series and parallel branches, current, resistance, and voltage to solve an authentic, personally motivating problem helped students activate conceptual understanding of physics related to electric circuits, as well as expand their knowledge of teaching and learning.

Although the scores were statistically unchanged on the final exam, which included optics, we have much less evidence of the effect on students’ knowledge of optics, as only three students elected a project that exclusively involved optics (a cell phone image projector, a telescope, and a prism ornament.) As is evident from the abundant research literature on e-textiles and other applications of electric circuits in Making, this content area is a particularly fertile area for Maker projects, where opportunities are readily available for students to encounter core content and skills. It is unclear how our results on incorporating Making

will translate into other areas of the physics curriculum, e.g., kinematics or thermodynamics. It may be that the study of electric circuits provides a “sweet spot” for Maker teacher education in the physics curriculum.

Further, the personal engagement promoted by the Maker project resulted in enjoyment and accomplishment. Beyond the constraint of involving electric circuits or optics, students were given leave to select a project of interest or of use to them and not required to use particular tools or equipment (e.g., 3D printers, controllers that require extensive coding, and other standards of Making such as “rockets, robots, and drones”) [55]. Students were able to engage in familiar practices, positioning them as capable and knowledgeable from the start. At the same time as they learned to use new tools, they learned to appreciate their own skills and knowledge, and those of the communities to which they belonged [9]. This is critical in the case of students who are not *a priori* interested in physics, and particularly important for students who are in-service and preservice teachers, who will go on to provide many K12 students with their only experience of physics.

The promise of Making to democratize invention and enable agency in the production of goods depends on access. Universal and free access to Making will only be achieved by situating it where students already are—in required coursework in public schools [1,14]. But not every K-12 school (and certainly not every physics class) has access to the expertise needed to support all student Makers, particularly in free-choice projects. If Maker resources are only available to students who already have the social and cultural capital for success in STEM and whose communities can afford high-cost and high-tech equipment, then Making might actually serve to increase educational inequities [3,6].

One way to enhance the potential for Making in K12 schools is through teacher education. If teachers have experienced success in Making, particularly in lower cost, lower-tech ways that take advantage of their own skills and interests, they are better equipped to promote it and enact it in their own classrooms. Preservice and in-service teachers in our sample had such an experience and became part of a classroom community of Makers, a potential network to support them in the future. Thus, we also see promise for

teacher education as a sweet spot in promoting access and to STEM learning and identity building through Making.

One limitation of our results is the lack of diversity in the population studied. Although just over 40% were students of color, these students could be considered to already have the social and cultural capital for success in STEM by virtue of being enrolled in a selective university, where automatic undergraduate enrollment at the time of the study was limited to the top less than 10% of graduating high school seniors in the state, and enrollment in STEM programs was even more restricted. Even though many came from districts where most students would not go on to college, they had already experienced at least that level of success.

Of course, an even more significant limitation is that we have only very limited evidence about how the teachers in our study went on to engage in Making in their classrooms or lives. As such, the results can only suggest the promise of Making to expand the benefits of greater engagement in physics learning to the many K-12 students our students will go on to teach. Regardless, our results show the potential of Making to increase the joy students find in physics and their ability to activate conceptual knowledge, at least in the area of electric circuits, without diminishing the success of an established, research-based curriculum. This possibility warrants further research in other content areas and with other populations.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available because of legal restrictions preventing unrestricted public distribution. The data are available from the authors upon reasonable request.

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