MakerCards: Designing An Electronic Component Discovery Tool to Support Remote Physical Computing Education

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Figure 1: MakerCards is a learning tool for instructors and students working with electronics.

ABSTRACT

Traditionally, the setting for maker education has been a physical space where students can engage in hands-on learning and often work collaboratively. However, as many schools adopt a remote learning model due to COVID pandemic conditions, a pressing need has arisen for instructional practices and tools that facilitate project-based distance learning. This work in progress presents the design process of a QR-code enabled learning tool for instructors and students working with electronics in introductory physical computing courses. Through iterative learning design research and deployment in two 3-week micro courses, we uncovered preliminary evidence for the versatility of tactile card decks in supporting disciplinary based learning behaviors, debugging practices, visual and remote communication, as well as the opportunities for enhancing knowledge transfer enabled through digital augmentation.

CCS CONCEPTS

• **Applied computing** → **Distance learning**.

KEYWORDS

learning design, physical computing, making, cards

IDC '21, June 26–30, 2021, Online

ACM ISBN 978-1-4503-8452-0/21/06.
https://doi.org/10.1145/3459990.3465196

ACM Reference Format:
Miranda Luong, Daragh Byrne, and Marti Louw. 2021. MakerCards: Designing An Electronic Component Discovery Tool to Support Remote Physical Computing Education. In *IDC '21: ACM Interaction Design and Children (IDC) conference, June 26–30, 2021, Online.* ACM, New York, NY, USA, 7 pages. https://doi.org/10.1145/3459990.3465196

1 INTRODUCTION

Maker-based education has become a highly popular form of instructional practice in recent years [12, 17]. Blending practices across hands-on, material led inquiry, with new digital technologies like Arduino and 3D printing, it encourages students to develop applied expertise through self-directed projects [9, 15]. A key, and much studied, component of this mode of educational inquiry is the spaces that support them [25, 36]. In much the same way as design studios [32, 33], makerspaces as designed environments play a vital role in building learning cultures that emphasize experiential learning, discovery and collaboration [9, 13]. The configuration and layout is oriented around informal learning, knowledge and feedback exchanges, and materials exploration. In particular, makerspaces are typically organized to visibly highlight the tools, materials and components available to learners in their project work [19, 35]. Component bins, tool chests, and other displays both make tools accessible and signal possibilities for project work and encourage exploration. In doing so, the space affords learning — structured and unstructured — about tools and processes.

The COVID-19 Pandemic and global stay-at-home orders have forced rapid adaptations to the delivery of educational experiences [10]. In particular, maker-based programs have faced significant challenges: spaces, project resources, technologies, and in-person interactions became inaccessible overnight [14]. Educators and makerspace leads have had to quickly navigate alternative instructional practices, substitute material resources, and develop creative strategies to triage the missing affordances of physical settings and the delivery of courses ill-suited to remote and hybrid learning.

We offer a case study and preliminary findings from one such response. Working closely with the main instructor of a physical computing makerspace's introductory and interdisciplinary courses, our design and learning research team, focused on improving in-situ access to and diffusion of knowledge around components and materials. The challenges of learning about electronic components are well-documented, and in particular for novices who need to successfully navigate many choices and identify appropriate parts for their projects [11, 16]. Yet is critical to progress and creative outcomes. In response, we prepared a low-cost, replicable and easy-to-disseminate learning tool for physical computing education that can be extended by others: a tangible card deck that depicts components found in the course kit and are linked to learning resources through a QR code. This builds on prior work in accessible resources for electronics education [1, 3, 6]. We report initial findings from its adoption in two three-week micro-courses during Fall 2020. The study examined how the cards were used by the instructor to introduce components, how they supported student learning (e.g. parts identification, wiring layouts, and debugging), and their role in exploring and communicating project ideas within hybrid-learning contexts. Findings suggest it is a versatile tool for instructional delivery, peer-to-peer communication,creative exploration, and knowledge acquisition.

2 BACKGROUND

Physical computing education focuses on teaching the preparation of interactive artifacts using integrated circuits, sensors and actuators. Given the material rich and tactile nature of physical computing, it is normally a spatial, situated, in-person instructional practice [26, 27]. Studies note this stems from the organizational complexity involved; introducing hardware, tools and hand skills (e.g. identifying componentry, soldering, wiring, microcontroller programming, circuit debugging), accessing specialized materials, storing projects between classes, and supporting joint activity [24, 26, 27]. Frequent hardware issues students encounter include incorrect circuit formations, pin connections, orienting of small parts, and parsing visual cues (e.g. color significance) [5]. Others note that novices need most help and improved support in "constructing circuits correctly, and diagnosing errors and implementing appropriate fixes" [2]. Instructors face additional and complex motivational challenges in introductory courses. Novices are often uncomfortable with programming, struggle with problem-solving, and find it hard to communicate ideas effectively. They must quickly master domain knowledge, identify and bridge abstract representations in working circuits, adopt computational thinking, and apply ideas in project work [2, 5, 24, 28, 34]. Attending these issues is challenging for instructional designers. This complexity is increased in the delivery and preparation of virtual makerspaces [24].

Tangible Cards & Thinking Tools: Physical card sets have been widely used as creativity support tools in design practice and education. They afford a low-cost, highly graphic way to manipulate and organize information that can be easily exchanged, flipped and rearranged to create new selections and juxtapositions of information. Roy and Warren [30] recently surveyed over 150 card decks that are currently available for use by design practitioners. Examples include 'Design with intent' [20], 'PLEX' [21] and 'The thing from the future' [4]. Cards decks to support domain-relevant physical computing IoT education have also appeared. These decks typically aim to solve specific challenges for learners, such as identifying problems, offering inspirational resources, developing technical know-how, generating ideas, and planning implementations of projects [18]. Examples include the Tiles IoT Deck [23], Futurice's IoT Service Kit [7] and in 2014, Aspiala and Deschamps-Sonsino developed KnowCards — from which we draw significant inspiration — to help non-experts develop technical know-how of electronic components [1]. Root et al. [29] noted a limitation of KnowCards is that they do not include guidance or instructions on how to program these components. They adopt a larger card size to incorporate programming information but students found the cards text-heavy, cumbersome, and used the cards primarily to select parts [29]. Our work seeks to address the perceived shortcomings in [1] and [29].

3 DESIGN PROCESS

As learning transitioned to remote instruction, we began a close collaboration with the instructor of the aforementioned physical computing lab. Grounded in learning design, our design research effort sought to find low-cost instructional toolkits to remediate the challenges of teaching electronics remotely, a subset of which are illustrated to the right. We began needs elicitation sessions with the instructor. The instructor described the course as a practical introduction to electronics that focuses on developing the functional knowledge of someone new to the Arduino microcontroller. Due to remote conditions, most students would attend class with a setup consisting of a desk, a laptop or computer, and their course kit (a commonly available set of standard electronic components).

The instructor was primarily concerned with the challenges of introducing students to a broad range of components, and the technical resources needed to operate them. It would be difficult for the instructor and students to inspect and navigate circuitry together when remote. If a student were to encounter a problem, the instructor would be unable to directly handle their circuitry or easily point at specific areas. Consequently, explaining technical concepts ad-hoc was expected to be challenging. Secondary concerns included promoting creative exploration. It was noted that component choices for projects were limited. Students would also lose the opportunity to explore components contextually; parts bins in the physical computing lab are commonly organized by category, behavior, or action. Lastly, the rich opportunities for communication and collaboration normally found in a makerspace would not be available. The solution space was further constrained by the need to rapidly produce a solution, the costs to ship to students around the world, as well as, avoiding complex assembly or uncertain technical infrastructures. Augmented cards were ultimately identified as a solution that satisfied these criteria and needs.

Inspired by Tina Aspiala and Alexandra Deschamps-Sonsino's KnowCards [1], we prepared a card deck specific to the parts in the

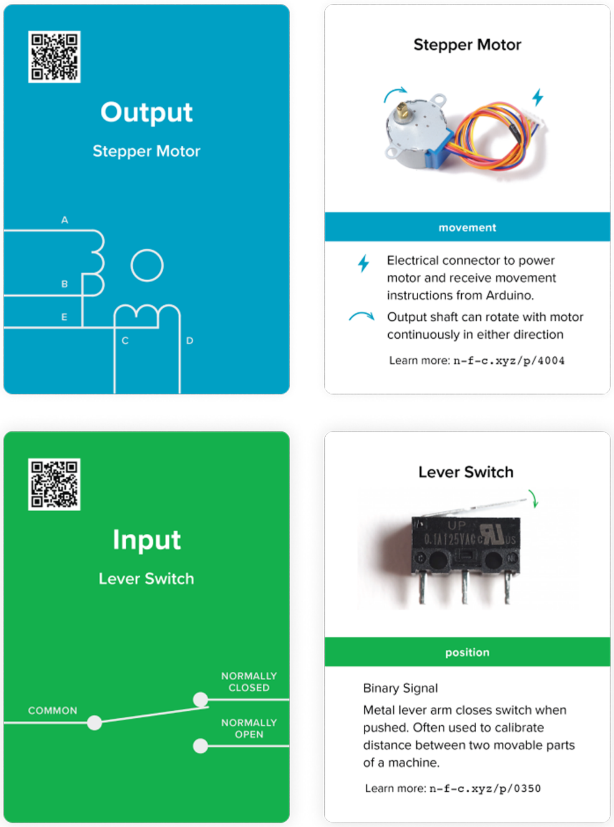

Figure 2: Two example cards back and front.

instructor's course kit (see Figure 2). The Maker Card primarily offers key information of each electronic component found in the kit, packaged in a comprehensive but accessible format. Three design iterations were prepared to extend prior work [2] and in order to help novice learners to:

- Become familiar with common physical computing components and their categorical types
- Recognize and notice small, salient details about the operational features, mechanisms and wiring of electronic components
- Support conceptual abstractions and mapping physical characteristics to electrical operation and schematics
- Increase a learners facility for rapid iterations in planning circuits and communication of project ideas
- Encourage systems thinking and ideation by emphasizing the categorical interchangeability of component parts
- Provide easy access to relevant online information resources and exemplars that encourage experimentation with those components, which can be accessed in-and- out-of class

Noticing Salient Details: In their simplest enactment these cards act as reminders of the same key information offered by the instructor in the first class. In this way, they help students to build greater familiarity and fluency with key components. In the design

Figure 3: The Maker Cards feature a QR Code that link learners to digital guides and starting points.

of these cards, we followed suit of the KnowCards and included categories to encourage students to learn the similarities between components. By color-coding these categories, we wanted to highlight the greater context that these individual components belong to. For complicated components, we annotated the images with richer depictions to highlight salient details of its mechanisms. The illustrations call out functionality or behavior of the part and is linked to the textual descriptions.

Supporting Circuit Abstractions: A key skill in physical computing is abstraction [2]. We added three abstractions of the physical component to the back of the card. At the highest level of abstraction is the component's category of function: input, output, controller, power or connection. Next, is the component's name and lastly, its schematic representation. These three levels of abstraction help guide a students' understanding and diagramming of an electronic circuit that is often very complex. To help students build a greater association between the physical components and their schematic symbols, we designed the pins of each schematic to lead off the edge of the card. Students can then start building their own circuit schematic by simply drawing a line between pins of two different cards, thereby connecting the schematics of the components.

Web Catalog: We also included a unique QR code and URL that links students to a webpage offering extensive information on the component including starter code and wiring diagrams (see Figure 3). The catalog also addresses the challenges of help seeking in remote contexts. Although many online forums exist to support electronic help seeking, they are diverse, scattered assemblages. It is challenging for novices to identify appropriate sources of online support [16, 19]. This instructor-managed web catalog is curated for novices, their information needs, and anticipated projects.

4 STUDY DESIGN AND DEPLOYMENT

The purpose of our preliminary study was to explore the cards as an instructional and creativity support tool and examine the use of the MakerCards in remediating the challenges of hybrid teaching and learning. In particular, we were interested in what instructional practices the cards supported, how they affected learning activities (e.g. parts identification, wiring layouts, and debugging) and finally, how they might be adopted and integrated into class communications and interactions around project work.

We deployed the MakerCards in an introductory skills development micro-course (3-weeks) open to both graduate and undergraduate students with no prerequisites. The micro-course covers the basic technical skills (electronics, programming, and hardware) needed to prototype simple interactive objects using Arduino. It meets over three weeks for three one- to five-hour sessions and pre-recorded content to review before class. One section took place in October 2020 and the other in November 2020.

Session 1: Before class, students receive a course kit and review pre-recorded lectures. During class, the instructor familiarizes the students with the components in their kits, and how to integrate physical inputs and outputs.

Session 2: In the second meeting (one hour), they review content and questions on practice assignments. The final project is introduced and students develop a plan.

Session 3: The final class is a five-hour work session for students to build a project of their own design with Arduino. The majority of time is used for technical experimentation. Students present projects to the class.

Due to COVID-19 restrictions, the micro-course was offered in a hybrid format with students attending both in the makerspace and synchronously via Zoom. For our study we observed two sections, one with 12 students (6 in-person, 6 remote), the second with 7-students (1 in-person, 6 remote). Four international students did not get physical MakerCards. These students were provided a digital version of the card deck using playcard.io. We observed each course session via Zoom to see how the tool supported instruction and impacted student's learning experiences. At least one member of the research team conducted observations, and kept field notes. Later, the session recording was reviewed to extract salient moments as screenshots paired with transcribed audio and research notes. We attended in particular to instructional practices involving the MakerCards, and student use of the cards. A weekly survey was also administered to the students and to the instructor. This included five questions that asked them to how they had used the cards and/or online resources during the past week, invited them to report a moment or experience of note, and encouraged them to provide reflections on how it helped or hindered learning. Finally, we conducted a debrief interview with the instructor.

5 PRELIMINARY FINDINGS

Our initial analysis is framed from an instructional-perspective and drawn from a combination of in-class observation, instructor feedback, web analytics. We analyzed the qualitative sources (annotated sessions transcripts and instructor survey responses) separately using an iterative, bottom up coding approach to identify emergent themes. We later aggregated the sources around three aspects of interest: how the MakerCards helped students to notice and recognize salient details of components, how the cards supported abstraction, and finally their role as a creativity support tool in exploring, presenting and debugging circuit-based projects. Independently, web analytics were analyzed for patterns of use and survey responses were coded for references to the web catalog. A summary of observations, insights and practices that developed are presented.

5.1 Supporting Recognition

MakerCards were used by the instructor to introduce the electronic components students received in their course kits. By pairing individual parts with the matching cards, the instructor could quickly highlight general functionality and offer comparative visual depiction, and then flip over the card to show a high-level schematic depiction and low-level terminal connections. Using a document camera feed, the parts and card setups were projected to students in the classroom and transmitted via Zoom (see Figure 4 top). With the schematic view at hand, students were able to match up parts and see similarities between different components in terms of current flow. By placing the frontside of the MakerCard next to a component, the instructor was able to visually and textually reinforce his explanations of the component's functions and features: "I think that by having clear reference sources for each part in the kit, I was able to help students much more quickly learn the names and general functions of each one." Labeled photographic images of parts enable easier perceptual recognition of smaller details such as pin position, mechanism, binary or analog signals, and the operation of a components' discrete mechanisms (see Figure 4 middle).

5.2 Supporting Abstractions

The color-coded categories for basic component types (input, output controller, connection, power) offers a quick visual abstraction for students to quickly interpret each component's fundamental role in a circuit. Coupled with their schematic representations, this allowed the instructor to easily demonstrate how inputs, outputs, and power flow through a circuit (see Figure 4 bottom): "The system of schematic symbology became much easier to refer to, and manipulate, through use of the cards. I was also able to, in a similar level of abstraction, build up general ideas of how circuits are properly constructed, by using multiple cards alongside each other to show, for instance, that a stepper motor needs to be interfaced 3 with the Arduino via a stepper motor driver; I just put the card in between the two to demonstrate how that would work"

5.3 Supporting presentation for critique and debugging

In the second session the instructor introduced block diagramming and a project planning exercise using the cards (see Figure 5). While planning their final project, some students used the MakerCards to not only develop their ideas, but also communicate the circuit layouts via Zoom for feedback. Others students did not have access to the cards which provided us with an opportunity to observe how students with and without the cards were able to present, interact and communicate around their projects via a video conferencing setup. Our observations below are based on the reflections of the instructor and our observations of student's class presentations. For students who drew project layouts or demo'ed them with physical components, communication was less fluid, we observed that they struggled with changes, and less engagement with the class was observed. The instructor noted that project plans and block diagrams demonstrated using the MakerCards were straightforward

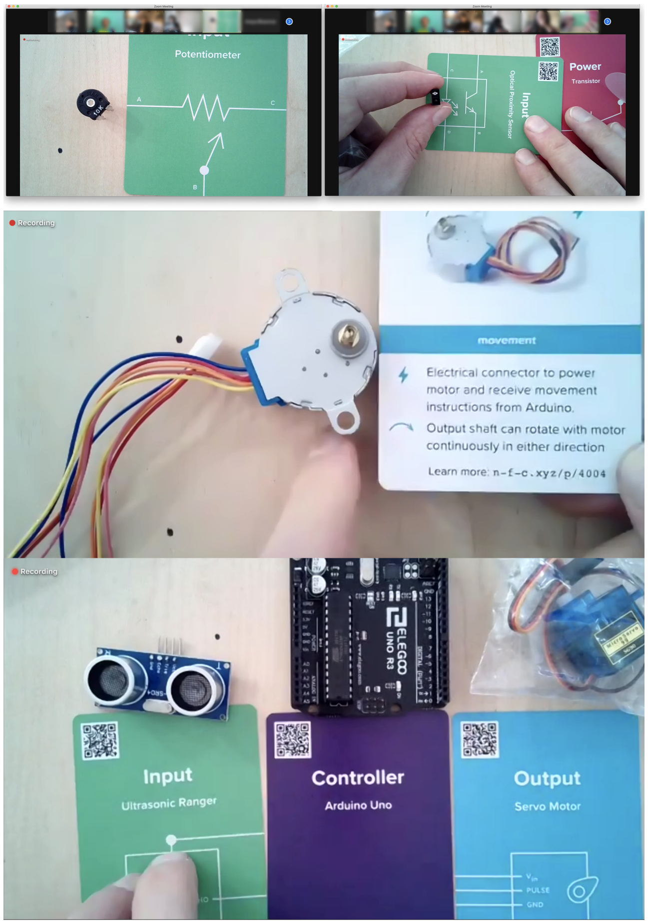

Figure 4: Examples of instructor demonstrations using the MakerCards. Top: Abstraction Using the backside of the card, the instructor demonstrates how a component's physical pins corresponded to those represented in its schematic. Middle: The photo on the card is compared to the actual components. Bottom: The instructor demonstrates schematics and relationships between inputs and outputs

for beginners to understand and share: "I believe that giving the students the physically manipulable cards gave them an opportunity to think in a broader sense about the structure and design of the final project they were proposing for the course." Even though the majority of the class was still gaining familiarity with electronic componentry, we observed that having contextual part information on view aided student comprehension and clarity of communication. Those students with cards had increased fluency with parts and in communicating their ideas: "The arrangement of the cards, I think, helped uncover and clarify the true flow of data through their project." It was rather easy for students and instructors to tweak the card-based circuit diagrams: "I could simply arrange the cards properly to illustrate an idea, knowing that students were able to easily and quickly imitate me in doing that if they wished." During the video call, the instructor was able to highlight mistakes and illustrate misunderstandings by asking the students to

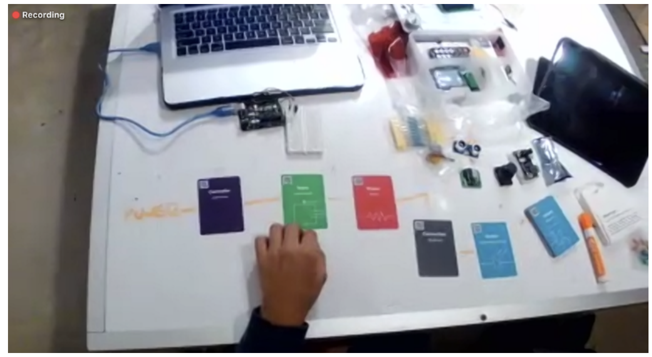

Figure 5: A student presents their block diagram project plan using the Maker Cards.

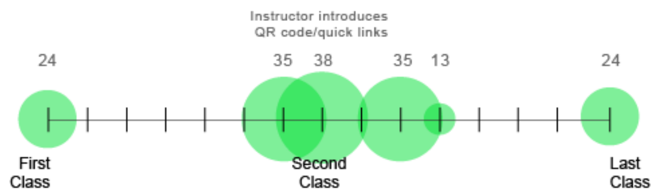

Figure 6: QR Code usage by students in the second cohort.

rearrange cards. This increased understanding of abstractions and demonstrated opportunities and approaches to problem-solving.

5.4 Digital Resources

An online web catalog of parts and resources was made available to students. The instructor introduced this to students in the second class as they began to plan and select components their final projects. Depicted in Figure 6 of five students and their interactions with this catalog. In reviewing web analytics, we noted an increase in use after its introduction which continued into the third week as students were preparing their final project. Steady out-of-class in Week 2 suggests the web resources offer a scaffold for independent exploration and experimentation of electronic components. During the class hours in the final build session, we also noticed student activity continued suggesting they were consulting these guides and starting point pages to scaffold towards their final projects. Anecdotal evidence from the instructor supports this: "Several students showed me that they were using the Maker Card web resource to find starter code...;" "I was pleasantly surprised to find that students were using the Maker Card website as a first-try reference source." These early results are encouraging but further analysis of the role the web resources play in student learning is required. This will be the subject of future work. Many opportunities for polishing the site resources were also identified. Recommendations included providing additional guidance for required libraries, highlighting common pain points, and providing examples of use in past student projects. Improving these web resources will be the subject of future work.

6 DISCUSSION AND FUTURE WORK

We have outlined the iterative design and an exploratory investigation of an augmented card deck for physical computing education. This was prepared in close collaboration with an educator responding to exceptionally challenging instructional circumstances. We hope our work helps to further characterize physical computing as a complex instructional practice that moves in real-time across visual, material and conceptual domains of learning and that merits further study.

The MakerCards also extend over prior precedents [1, 29] to directly link the cards with the just-in-time access to knowledge assets needed to gesture, act and think with. This is a small but important innovation in developing epistemic tools [22, 31] that greatly benefited teaching and learning. We observed the instructor being able to model and communicate expert practices in electronics – from close looking to inspect parts, to fluidly rearranging schematic diagrams – allowing those skills to be replicated by a novice cohort. We also note that the added schematic diagrams appeared to positively affect abstraction and systems thinking, as well as, offering novices much needed supports [2] in preparing circuits, in diagnosing errors and in fixing mistakes. Moreover, our initial observations suggest the cards could function as lightweight creativity support tools for quick exploration and comparison of circuit implementations and for navigating design choices for the students' applied projects. We are extremely encouraged by the observed efficacy by which instructors and students were able to communicate ideas, point and debug project plans with verbal/visual precision through Zoom with the cards. This suggests they offer a potentially rich resource for distributed collaboration and coordination and for developing professional vision [8] in situated practice. This will be the subject of future work. We also acknowledge our preliminary findings are instructor-centered and we intend to scale the approach to a full-semester course and a student-centered evaluation in order to better understand their experience with the MakerCards and the tool's effects on self-efficacy, on acquiring domain knowledge and practices, and on communication and collaboration in hybrid learning environments.

Finally, we note that this case study highlights the value of ubiquitous, accessible technologies, namely QR codes, in rapidly addressing needs in challenging educational contexts. The significant challenges posed by COVID-19 to educators remind us that purposefully adopting familiar lower-cost technology in new contexts can have a significant impact. Coupling ready-at-hand cards web resources through QR codes offers simple, scalable, accessible, and adaptable solutions that are generally well understood by users, that can be deployed in diverse learning contexts, and that support a range of learning formats, and instructional goals. This is in contrast to the many high technology solutions that have recently emerged. We plan to experiment with the opportunities this strategy affords as part of next steps.

ACKNOWLEDGMENTS

We would like to thank our student participants for their feedback and Robert Zacharias for their considered input and feedback throughout the cards design, development and deployment. This material is based upon work supported by the National Science Foundation under Grant No. 1736189 "Smart Spaces for Making: Networked Physical Tools to Support Process Documentation and Learning."

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